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Evaluation of Combustion Modification Effects on Emissions and Efficiency of Wood-Fired Industrial Boilers

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EVALUATION OF COMBUSTION MODIFICATION EFFECTS ON EMISSIONS AND EFFICIENCY OF WOOD-FIRED INDUSTRIAL BOILERS

by

R. J. Tidona, W. A. Carter, H. J. Buening, and S. S. Cherry

KVB, Inc.
18006 Skypark Boulevard
Irvine, California 92714

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EPA Project Officer: Robert E. Hall

Industrial Environmental Research Laboratory
Office of Environmental Engineering and Technology
Research Triangle Park, NC 27711

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16. ABSTRACT The report gives results of full-scale tests to evaluate combustion modifications (lower excess air and variations in the overfire air system operation) for emission control and efficiency enhancement on two wood-fired industrial boilers. One boiler, rated at 100,000 lb steam/hr, is fueled with a combination of wood bark and coal. Implementation of lower excess air reduced NOx emissions by 18.5 percent and improved thermal efficiency by 0.89 percent. Variations in the overfire air system reduced NOx by 20.7 percent and improved efficiency by 1.63 percent. The second boiler, rated at 200,000 lb steam/hr when fired with hogged wood, can achieve 250,000 lb steam/hr when fired with hogged wood and an oil supplement. The effectiveness of lower excess air in reducing NOx was about 14 percent with a slight (0.6 percent) improvement in efficiency. Adjusting the auxiliary air dampers reduced NOx by 17.2 percent and improved efficiency by 1.7 percent. Polycyclic organic matter (POM) was sampled at both baseline and optimum low-NOx conditions. Under baseline conditions, POM emissions were similar to those of a coal-fired spreader stoker and an oil-fired boiler, but were well below those of a pulverized-coal-fired boiler tested previously. For the wood-fired boiler, POM emissions in the low-NOx mode were higher than those at baseline.

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Combustion	Dust	Stationary Sources	21B	11G
Wood	Industrial Processes	Combustion Modification	11L	13H
Fuels	Particle Size	Particulate	21D	14G
Fossil Fuels	Stoichiometry	Overfire Air		07D
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ABSTRACT

Results of full scale tests to evaluate combustion modifications for emission control and efficiency enhancement on two wood-fired industrial boilers are reported. These modifications consisted of lower excess air and variations in the overfire air system operation.

The boiler at Location 3 is fueled with a combination of wood bark and coal. The implementation of lower excess air reduced NO_x emissions by 37.2 percent and improved thermal efficiency by 1.2 percent. Variations in the overfire air system reduced NO_x by 20.7 percent and improved efficiency by 1.6 percent. The combination of lower excess air and overfire air system modification reduced NO_x by 18.5 percent and improved efficiency by 0.9 percent. A 51 percent load reduction produced only a 3.7 percent NO reduction and a 4.0 percent loss in efficiency.

The boiler at Location 5 uses hogged wood as the primary fuel and oil as the supplemental fuel. The effectiveness of lower excess air in reducing NO_x was 12.5 percent with a slight improvement in efficiency (0.6 percent). Adjustment of the auxiliary air dampers produced a 17.2 percent NO_x reduction and a 1.7 percent improvement in efficiency. Polycyclic organic matter (POM) sampling was performed at both baseline and optimum low-NO_x conditions. On a $\mu g/m^3$ basis the POM for low-NO_x conditions exceeded the baseline results by a factor of two to three. The results obtained are compared to previous sampling on industrial steam boilers.

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Limitations on Application of Data Reported

The pollutant emission data cited in this report pertain to two specific wood boilers. These data should not be used to estimate mean emissions from other types of wood boilers or to predict emission reduction potentials of combustion modifications until the modifications have actually been carried out on a greater number of such combustion types.

SECTION 1.0

INTRODUCTION AND SUMMARY

This report is one of a series which describe tests of combustion modifications to control NO_x emissions from industrial process equipment. This work was performed under EPA Contract No. 68-02-2645 over the time period from August 1977 to June 1981.

The activities reported herein include tests performed on a wood bark/coal-fired boiler (Location 3) and a hogged wood fuel boiler (Location 5). Oil was the supplemental fuel at Location 5.

Variations in load, excess air and overfire air were the combustion modifications common to both boilers. In addition, lowering combustion air preheat and positioning of the supplemental fuel oil air damper were performed at Location 5. Polycyclic organic matter (POM) sampling was also conducted at Location 5 at both baseline and optimum low-NO_x conditions.

Table 1-1 summarizes the reductions in NO and changes in efficiency measured at Location 3 for each of the combustion modifications. The overfire air system modification consisted of increasing each of the overfire air ports from 1 inch (2.54 cm) to 1-1/2 inches (3.81 cm) in diameter. As shown in Table 1-1, the lowest NO level obtained resulted from implementing lower excess air before the modification of the overfire air ports. This arrangement also produced an increase in boiler efficiency of 1.2 percent.

Table 1-2 summarizes the NO reductions achieved at Location 5 and the change in efficiency for all modifications except reduced combustion air preheat. This modification could not be fully implemented since the combustion air temperature could only be reduced by 16 - 22 K. Also noted in this table is the NO mass emission factor measured after each modification had been implemented.

Of some interest for this particular boiler is the effect of load changes on NO emissions. As noted, increasing load (18 percent) actually

TABLE 1-1. SUMMARY OF COMBUSTION MODIFICATIONS AT LOCATION 3

Control	NO Reduction, %	Efficiency Change, %	NO After Control ng/J*
Lower Excess Air† (146)††	37.2	+1.2	92
Lower Excess Air§ (184)	18.5	+0.9	150
Overfire Air Dampers§ (174)	20.7	+1.6	138
Load Reduction (51%)§,# (140)	7.9	-4.0	129

*NO as NO_2.

†Before overfire air system modification.

§After overfire air system modification.

#Load reduction referenced to nominal operation at 80% of rating.

††Value in parenthesis is baseline NO (ng/J) before combustion modification.

TABLE 1-2. SUMMARY OF COMBUSTION MODIFICATIONS AT LOCATION 5

Modification	NO Reduction, %	Efficiency Change, %	NO After Modification ng/J*
Lower Excess Air (40)§	12.5	+0.6	35
Increase Overfire Air (46)	21.7	-1.3	36
Auxiliary Air Damper (36)	17.2	+1.7	30
Load Change†			
+18% (40)	27.5	+0.9	29
-30% (40)	30.0	+1.8	28

*NO as NO_2.

†Load change referenced to nominal operation at 76.5% of rating.

§Value in parenthesis is baseline NO (ng/J) before combustion modification.

reduced the NO concentration and mass emission factor. This characteristic of peak NO occurring in the mid-load range is somewhat unusual.

Polycyclic organic matter (POM) samples were collected and analyzed at both baseline and low-NO_x (auxiliary air damper adjustment) conditions. The significant finding was that the total POM at the low-NO_x condition could be two to three times higher than that measured under baseline conditions. This large difference could be due more to fuel property variations than to combustion modification although the trend of higher POM with lower NO_x has been observed previously on a coal-fired spreader stoker (Reference 1).

SECTION 2.0

TEST EQUIPMENT DESCRIPTION

2.1 EMISSIONS SAMPLING EQUIPMENT

Gaseous emission measurements were made using analytical instruments and equipment contained in a government-furnished mobile instrumentation laboratory. A plan view of the trailer is shown in Appendix A. Total particulate measurements were made using an EPA Method 5 sampling train produced by Joy Manufacturing Company. Particulate size distribution was measured using a Brink Cascade Impactor. Total oxides of sulfur were measured by wet chemistry methods using the sampling train and analytical procedure of the Goksoyr-Ross method. Smoke density was measured using an automated Bacharach smoke spot pump. Stack opacity readings were made during particulate tests according to EPA Method 9.

2.1.1 Gaseous Emissions Sampling System

The laboratory is equipped with analytical instruments to continuously measure concentrations of NO, NO_2, CO, CO_2, O_2, SO_2, and hydrocarbons. The sample gas is delivered to the analyzers at the proper condition and flow rate through the sampling and conditioning system described below. Appendix A describes the analytical instrumentation and the details of the sampling system.

A flow schematic and description of the flue gas sampling and analyzing system is presented in detail in Appendix A. Briefly, the sampling system used pumps to continuously draw flue gas from the heater into the laboratory. A high-capacity heated positive displacement diaphragm pump was used to draw a high volume of flue gas into the analyzers to assure quick response to source variations.

Special precautions were required to obtain a representative sample for the analysis of NO_2, SO_2, and hydrocarbons. These precautions consisted of insuring that the sample was kept above its dew point, to prevent loss of

sample components in condensed water. For this reason, an electrically heated 9.5 mm (3/8 in.) Teflon sample line was used to bring the sample into the laboratory for analysis. The hot pump provided heated sample directly to the hydrocarbon, SO_2, and NO_x analyzers.

A portion of the sample pump discharge was also sent through a refrigerated condenser [to reduce the dew point to 275 K (35°F)], through a large rotameter with flow control valve, and then to the O_2, NO, CO, and CO_2 instrumentation. Flow to each individual analyzer was measured and controlled with smaller rotameters and flow control valves. Excess sample was vented outside the laboratory.

2.1.2 Particulate Emissions

Particulate samples were taken at the same sample location as the gas sample using a portable effluent sampler produced by Joy Manufacturing Company. These tests were made at baseline and optimum low-NO_x operating conditions. This system, which meets EPA design specifications for Test Method 5, Determination of Particulate Emissions from Stationary Sources (Federal Register, Volume 36, No. 27, page 24888, December 23, 1971) was used to perform both the initial velocity traverse and the particulate sample collection. Dry particulates were collected in a heated case that contained a 110 mm glass-fiber filter for retention of particles down to 0.3 micrometers. Condensible materials were collected in a train of four impingers in a chilled water bath.

Particle size was measured at baseline and optimum low-NO_x conditions at the same sample location as the Method 5 tests. A Brink Cascade Impactor was used for all of the sizing tests because of its high grain loading capability. This impactor was capable of fractionating particles in-situ into six aerodynamic size ranges (five collection stages and one backup filter). The size range capability of this impactor was approximately 0.4 μm to 10 μm.

The Method 5 sampling train and procedures, and the impactor operational procedures, are discussed in Appendix A.

2.1.3 Wet Chemical SO_x Measurement

The Goksoyr-Ross technique was used to sample the stack gas for SO_3. This method uses controlled condensation of the stack gases in a coil maintained at 333-344 K (140-160°F) by a water bath. This temperature is below the sulfuric acid (H_2SO_4) dewpoint so that the SO_3 and the water vapor in the flue gas condense upon the coil walls to form H_2SO_4 droplets. The SO_2 in the flue gas passes through the coil and is collected in impingers containing a weak hydrogen peroxide solution. Following the impingers, the flue gas flows through a dry gas meter and is then discharged into the atmosphere.

The coil rinse and impinger liquid are each analyzed by means of an acid-base titration with a sodium hydroxide solution. Both the SO_3 and SO_2 concentrations may be determined from this procedure.

2.1.4 Smoke Spot and Opacity Measurement

On combustion equipment where smoke numbers normally are taken, such as oil-fired boilers, the smoke number is determined using test procedures according to ASTM Designation: D 2156-65. The smoke number is determined at each combustion modification setting of the unit. Examples are baseline, minimum excess air, low load, etc., and whenever a particulate concentration is measured.

Smoke spots are obtained by pulling a fixed volume of flue gas through a fixed area of a standard filter paper. The color (or shade) of the spots that are produced is visually matched with a standard scale. The result is a "Smoke Number" which is used to characterize the density of smoke in the flue gas.

Opacity readings were taken by a field crew member who is a certified graduate of a U.S. Environmental Protection Agency approved "Smoke School." Observations are made at the same time that particulate measurements are made and as often in addition as deemed necessary to gather the maximum amount of information. The procedures set forth in EPA Method 9, "Visual Determinations of the Opacity of Emissions for Stationary Sources," were followed.

SECTION 3.0

WOOD BARK/COAL BOILER, LOCATION 3

3.1 BOILER DESCRIPTION

This boiler uses by-product wood bark from the plant's pulping operation and coal, or coal only. The unit was built in 1966 by the Wickes Boiler Company and is rated at 100,000 lb/hr (45.4 Mg/h) steam flow firing a combination of coal and bark or coal only. The boiler is equipped with a travelling grate spreader stoker. The wood bark is injected pneumatically above the three coal feeders through three ports located above the front overfire air ports. The smaller wood particles burn in suspension while the rest of the bark burns on the grate. Preheated combustion air is introduced under the grate after passing through a tubular air preheater. The unit is equipped with a multiclone dust collector. Figure 3-1 is a cross-section of a typical boiler used for suspension and thin-bed burning of wood. Figure 3-2 is a bark distributor which is similar to the three air-swept distributors used in the Location 3 unit. Other boiler characteristics are:

Maximum Continuous High Pressure Steam Output:	Firing coal and bark or coal only - 100,000 lb/hr (45.4 Mg/h)
Steam Conditions at Superheater Outlet:	Temperature - 800 °F (700 K) Pressure - 600 psig (4.14 MPa)
Heating Surface:	Boiler 11,247 ft^2 (1,045 m^2) Air Heater 6,060 ft^2 (563 m^2) Water Walls 1,768 ft^2 (164 m^2) Furnace Volume 6,150 ft^3 (174 m^3)

Bark flow rate to the boiler was controlled as well as possible. Flow fluctuations and interruptions occurred from time to time and are considered normal operation. The percentage of bark heat input was estimated from the steam chart when bark flow was interrupted.

The test unit was limited in the amount of wood bark being burned due to high superheat metal temperature. Whenever superheat metal temperature

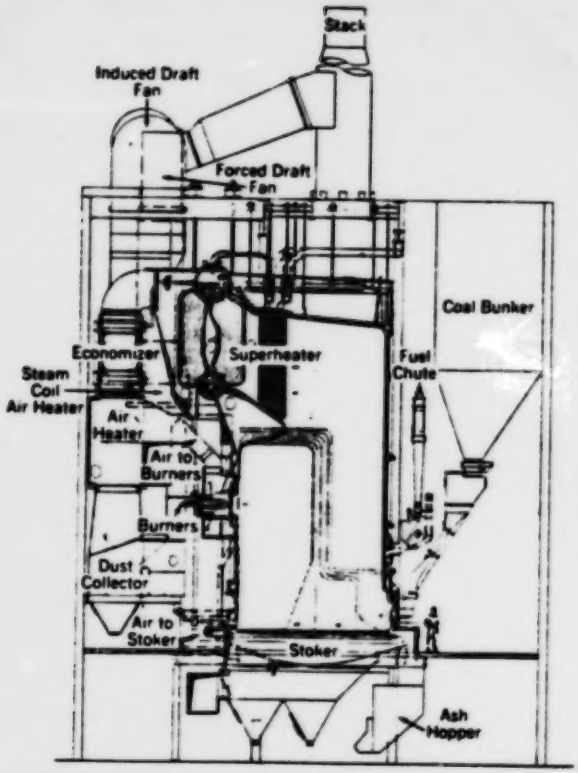

Figure 3-1. Two-drum Stirling boiler for suspension and thin-bed burning of wood.

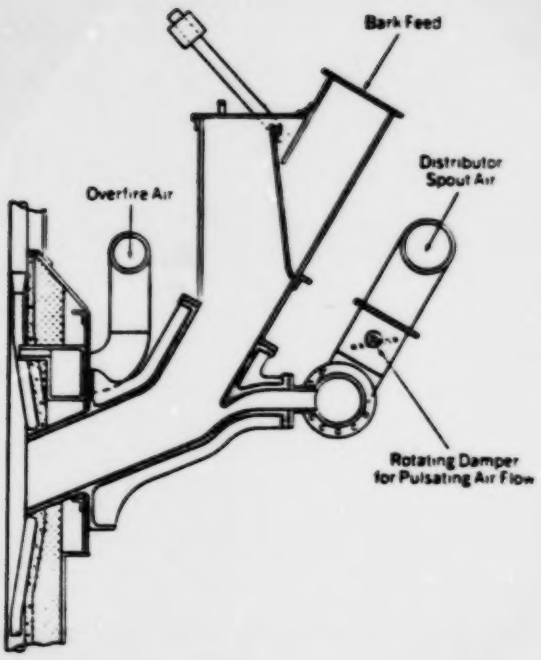

Figure 3-2. Air-swept distributor spout for spreader stoker.

reached 810°F (706 K), the bark flow was reduced until the tube temperature dropped below 800°F (700 K). The high superheat metal temperature is caused by the large amount of small bark particles which are injected above the front overfire air ports, burning in suspension above the grate near the superheater tubes. While burning coal only, the unit encountered no problem in maintaining the design superheat metal temperature of 750°F (672 K).

3.2 EMISSIONS SAMPLING

Gaseous and particulate emissions measurements were made at a single port in the duct work downstream of the multiclone dust collector and induced draft fan. A heated sample line was used to sample all gaseous emissions. No access was available for measurements upstream of the dust collector. During the test series problems were encountered with the heated sample pump and the problem could not be fixed at the test site. For test numbers 3-20 through 3-32 only cold line data could be taken. Therefore, neither NO_2, SO_2 nor hydrocarbons could be sampled or measured during these tests.

At the dust collector outlet a Lear Siegler Optical Transmissometer was installed by the boiler owner. The readings of this instrument were recorded in the control room data sheets.

Appendix A describes the instrumentation employed.

3.3 BASELINE TESTS

Baseline emission measurements were made with the boiler in the "as-found"* condition firing about 20 percent wood bark and 80 percent coal. All test results are summarized in Table 3-1. The results of the wet chemical SO_2/SO_3 measurements made during test 3-25 were:

SO_2--891 ppm (corrected to 3% O_2), 794 ng/J

SO_3--4 ppm (corrected to 3% O_2), 4 ng/J

---

*As-found relates to the unit operation at the time of the KVB test crew arrival. Baseline refers to the unit operating at its nominal conditions. As-found and baseline conditions are usually the same, however, they can differ.

TABLE 3-1. SUMMARY OF EMISSIONS FROM LOCATION 3 WOOD BARK/COAL BOILER

Test No.	Date 1979	Nominal Steam Load Mg/h	Nominal Steam Load 10^3 lb/hr	Heat Input Rate MW	O_2 %	CO_2 %	NOx ppm*	NOx ng/J	NO ppm*	NO ng/J	HC ppm*	HC ng/J	CO ppm*	CO ng/J	SO_2 ppm*	SO_2 ng/J
3-1	4/11	37.2	82	29.4	9.3	10.3	NOx Converter Out of Service	--	231	366	0	0	362	139	677	596
3-2	4/11	37.7	83	29.8	10.8	8.6		--	394	624	0	0	574	220	724	637
3-3	4/11	37.2	82	29.4	8.2	12.4		--	184	291	0	0	387	149	647	569
3-4	4/11	37.2	82	29.4	7.8	12.8		--	145	230	0	0	498	191	584	514
3-5	4/12	15.9	35	12.6	11.9	8.3	205	325	205	325	0	0	613	235	268	236
3-6	4/13	36.3	80	28.7	8.7	9.9	256	405	247	391	108	23	292	112	1062	934
3-7	4/16	25.0	55	19.8	10.1	9.8	202	320	198	313	206	44	1032	396	396	348
3-8	4/16	24.0	53	19.0	8.7	10.8	170	269	170	269	0	0	505	194	527	464
3-9	4/16	25.0	55	19.8	11.0	8.4	311	492	306	484	0	0	207	80	1728	1520
3-10	4/16	25.9	57	20.5	9.8	9.4	204	323	201	318	924	196	587	225	225	198
3-11	4/17	35.4	78	28.0	9.6	8.7	230	364	216	342	1895	402	268	103	1011	889
3-12	4/17	35.4	78	28.0	10.4	8.9	306	484	297	470	1995	423	304	117	1596	1404
3-13	4/17	35.4	78	28.0	10.6	8.1	438	693	415	657	1341	284	87	33	2769	2436
3-14	4/17	35.4	78	28.0	9.8	8.3	321	508	312	494	723	153	129	50	2507	2205
3-15	4/18	35.4	78	28.0	9.7	8.9	301	477	292	462	2506	532	288	111	1180	1038
3-16	4/18	35.4	78	28.0	10.4	7.7	310	490	306	484	6708	1423	450	173	645	567
3-17	4/18	36.3	80	28.7	9.2	7.6	231	366	227	359	4653	987	275	106	610	537
3-18	4/18	35.4	78	28.0	8.5	10.1	251	397	238	377	1728	367	238	91	864	760
3-19	4/19	35.4	78	28.0	9.8	9.0	275	435	275	436	849	180	493	189	1489	1310
3-20	4/19	35.4	78	28.0	10.0	7.7	----	--	221	350	----	--	319	123	----	--
3-21	4/19	35.4	78	28.0	9.6	7.7		--	229	363		--	308	118		--
3-22	4/19	35.4	78	28.0	10.6	6.8		--	243	385		--	243	93		--
3-23	4/19	34.9	77	28.7	9.9	9.5		--	218	346		--	154	59		--
3-24	4/20	34.9	77	28.7	9.9	8.9		--	222	352		--	292	112		--
3-25	4/20	29.5	65	23.3	8.8	10.2		--	168	266		--	465	179		--
3-26	4/23	37.2	82	29.4	8.2	10.2		--	192	304		--	192	74		--
3-27	4/24	37.7	83	29.8	9.6	9.8		--	212	336		--	391	150		--
3-28	4/24	38.1	84	30.2	9.4	10.2		--	178	282		--	472	181		--
3-29	4/25	18.2	40	14.4	11.9	7.5		--	205	325		--	828	318		--
3-30	4/25	27.2	60	21.5	10.8	8.6		--	214	339		--	281	108		--
3-31	4/25	36.8	81	29.1	9.3	9.5		--	221	350		--	230	88		--
3-32	4/25	46.7	103	37.0	9.1	9.9		--	268	425		--	364	140		--

Hot Pump Out of Service

TABLE 3-1. (CONTINUED)

Test No.	% $\dot{Q}$ Bark	Total Particulate lb/10^6 Btu	Total Particulate ng/J	Solid Particulate lb/10^6 Btu	Solid Particulate ng/J	Stack Temperature °F	Stack Temperature K	Eff. %	Comments
3-1	31					420	489	81.56	As found boiler test - high barkflow
3-2	31					430	493	79.77	O_2 variation - high
3-3	31					430	494	82.77	O_2 variation
3-4	31					440	500	82.55	O_2 variation - low
3-5	50					420	489	79.01	Low load - approx 50% barkflow
3-6	28	0.244	105	0.204	88	428	493	80.99	Baseline particulate - high barkflow
3-7	23					431	495	80.31	Medium load - approx 23% barkflow
3-8	23					417	487	81.78	Medium load, low O_2 - approx 23% bark
3-9	0					408	482	79.16	Medium load - coal only
3-10	24					435	497	79.88	Medium load - high barkflow
3-11	15					430	494	79.35	Baseline - low barkflow
3-12	15					428	493	79.70	High air - low barkflow
3-13	0					417	487	78.76	High air - coal only
3-14	0					410	483	79.46	Normal air - coal only
3-15	16	0.504	217	0.428	184	428	493	79.68	Baseline particulate - approx 16% bark
3-16	14					425	491	79.06	O_2 variation
3-17	6					431	495	77.22	O_2 variation
3-18	6					435	497	80.39	O_2 variation
3-19	15					431	495	79.19	Baseline - overfire air variation
3-20	15					432	495	77.72	Overfire air variation
3-21	15					435	497	77.61	Overfire air variation
3-22	15					431	495	76.86	Overfire air variation
3-23	15					429	494	80.48	Overfire air variation - low excess air
3-24	21					430	494	79.34	Low NOx - Cascade impactor
3-25	26					440	500	80.47	SOx test
3-26	16	0.320	138	0.274	118	437	498	79.31	Low NOx particulate
3-27	24	0.400	172	0.361	155	435	497	79.56	Baseline particulate - approx 24% bark
3-28	29					440	500	80.02	Baseline - Cascade impactor
3-29	10					420	489	76.42	Load variation
3-30	10					419	488	78.65	Load variation
3-31	10					420	489	79.61	Load variation
3-32	10					430	494	77.82	Load variation

*ppm corrected to 3% O_2

Also shown in Table 3-1 is the bark contribution to the total boiler heat input (with coal supplying the balance).

Fuel and ash analyses are presented in Table 3-2. Of note is the high carbon content of the bottom and fly ash. The boiler efficiencies noted in Table 3-1 include the loss associated with unburned carbon. Tests 3-1 through 3-6 were conducted with the original one inch (2.54 cm) overfire air nozzles. Tests 3-7 through 3-32 were run after the 12 upper and five lower overfire air ports in the back of the boiler were changed to 1-1/2" diameter (3.81 cm) to enlarge overfire air capacity and increase turbulence.

Boiler load during the test series was approximately 80 percent of rated load except for the load variation tests. NO emissions at the baseline condition were 146 ng/J or 231 ppm at 3 percent O_2. NO emissions as a function of O_2 before the overfire air nozzle modifications are shown in Figure 3-3. The smoke limit was found at 7.8 percent O_2 at a load of 82,000 lb (37.2 Mg/h) of steam per hour.

A baseline test (Test 3-11) immediately after the overfire air port modification showed 136 ng/J of NO or 216 ppm at 3 percent O_2. NO and SO_2 emissions increased as coal flow increased. Highest NO_x emissions occurred when only coal was burned, i.e., 196-277 ng/J (Tests 3-9, 3-13, and 3-14).

Solid particulate emissions during baseline conditions were measured with two different amounts of bark flow. The highest particulate emissions (184 ng/J or 0.428 lb/10^6 Btu, solid) occurred when approximately 16 percent of the fuel was made up by bark. At 25 percent bark flow solid particulate emissions decreased by 16 percent to 155 ng/J or 0.361 lb/10^6 Btu. Particulate size distribution was also measured using a Brink cascade impactor. Data on the size distribution are shown in Figure 3-4 for test number 3-28, where particle diameter as a function of cumulative proportion of impactor catch is plotted. Approximately 46 percent of the particulate is below 3 μm aerodynamic diameter.

TABLE 3-2. LOCATION 3 FUEL ANALYSES

Test No.	3-6	3-15	3-26	3-27	3-6	3-15	3-26	3-27
Date	4-13-79	4-18-79	4-23-79	4-24-79	4-13-79	4-18-79	4-23-79	4-24-79
Fuel Type	Coal	Coal	Coal	Coal	Wood	Wood	Wood	Wood
Ultimate Analysis								
Moisture, % weight	6.63	6.06	6.62	6.77	51.51	53.87	35.78	41.23
Carbon, %	64.89	66.12	61.83	62.60	25.58	23.93	33.59	31.01
Hydrogen, %	4.25	4.43	4.33	4.33	2.84	2.77	3.77	3.55
Nitrogen, %	1.48	1.53	1.45	1.50	0.16	0.17	0.17	0.20
Sulfur, %	2.36	1.96	3.01	2.30	0.030	0.029	0.025	0.026
Ash, %	8.94	8.46	12.20	11.07	1.51	1.42	1.61	1.56
Oxygen (diff.), %	11.45	11.44	10.56	11.43	18.37	17.81	25.05	22.42
Proximate Analysis								
Moisture, % weight	6.63	6.06	6.62	6.77	51.51	53.87	35.78	41.23
Ash, %	8.94	8.46	12.20	11.07	1.51	1.42	1.51	1.56
Volatile Matter, %	38.78	37.30	37.52	37.49	37.21	37.23	51.53	46.51
Fixed Carbon, %	45.65	48.18	43.66	44.67	9.77	7.48	11.08	10.70
Heat of Combustion								
Gross Btu/lb	12,050	12,160	11,580	11,470	8,950	8,890	9,060	8,890
Net Btu/lb	11,660	11,750	11,180	11,070	NR*	NR	NR	NR
Bottom Ash								
Carbon, %			11.56					
Gross Btu/lb			would not ignite					
Fly Ash								
Carbon, %	33.21		25.74					
Gross Btu/lb	4,370		3,590					

*NR = not reported by testing laboratory.

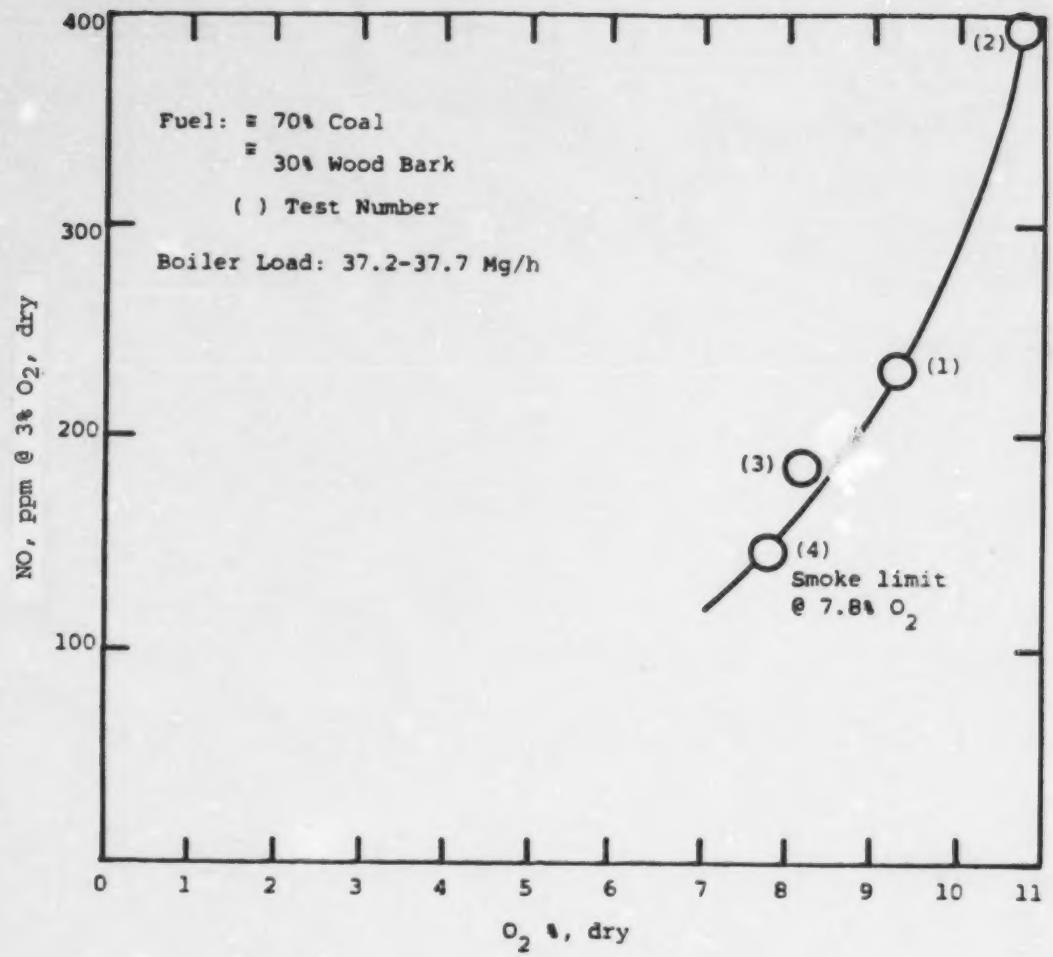

Figure 3-3. NO emissions as a function of O_2 before overfire air nozzle modification.

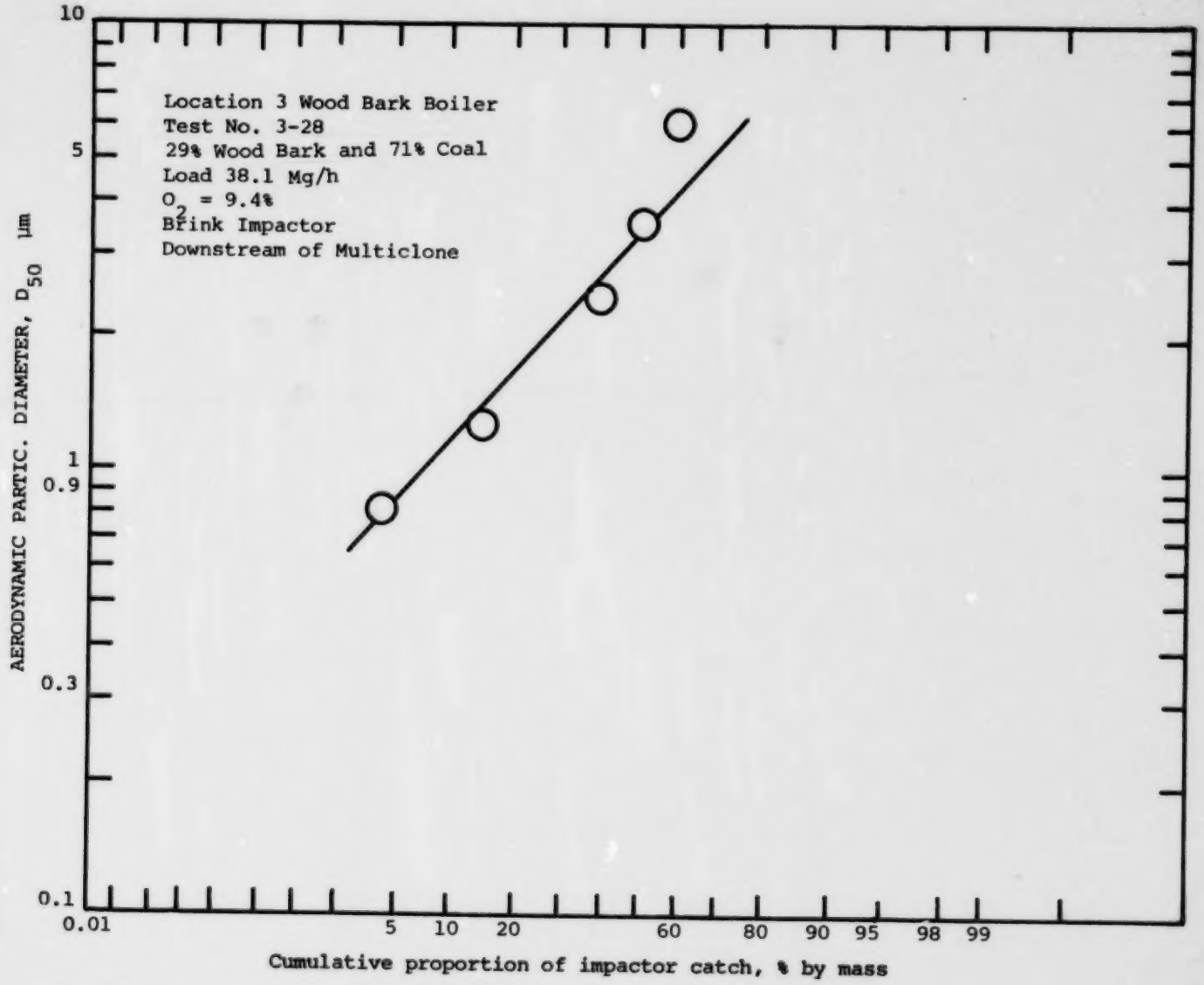

Figure 3-4. Aerodynamic Particle Diameter - Baseline Conditions

3.4 COMBUSTION MODIFICATIONS

Combustion modification testing included load variation, variation of excess air and overfire air adjustments with the modified nozzles described previously. NO emissions as a function of load are presented in Figure 3-5.

A test series (Tests 3-15 through 3-18) was conducted to evaluate the effect of stack oxygen on NO emissions. The overfire air was left constant - 100 percent open which is normal for these tests. Stack O_2 was controlled by adjusting the damper on the forced draft fan which supplies the undergrate air. The baseline condition for the O_2 variation (Test 3-15) was 9.7 percent O_2 with 184 ng/J of NO emissions. Stack O_2 during these tests varied from a high value of 10.4 percent to a low value of 8.5 percent. The effect of stack O_2 on NO emissions is shown in Figure 3-6 which includes all the test data measured. Lowering the stack O_2 resulted in a decrease in NO from 193 ng/J at 10.4 percent O_2 to 150 ng/J at 8.5 percent O_2. During the duration of the low O_2 test no clinkering was observed and combustion conditions appeared to be good.

After the O_2 variation test series the boiler was returned to the baseline condition to provide a baseline check point for the overfire air tests. The dampers for the two overfire air headers in the back of the boiler were set in their normal position which is 100 percent open. The fly ash reinjection headers were also in their fully open position. The front overfire air dampers were 30 percent open for the upper header and 90 percent open for the lower header. At baseline conditions (Test 3-19) NO emissions were 174 ng/J with 189 ng/J CO emissions. The dampers for the lower row of overfire air jets and for both fly ash reinjection headers were reduced to 50 percent open. NO emissions at this test point (Test 3-23) dropped to 138 ng/J with 59 ng/J of CO.

During the test series, it was observed that the SO_2 measurements were varying. This was due to fluctuations in wood bark flow. At a stable load condition whenever bark flow decreases more coal is automatically fed onto the grate to keep the load steady. The higher coal flow then increases the SO_2 emissions.

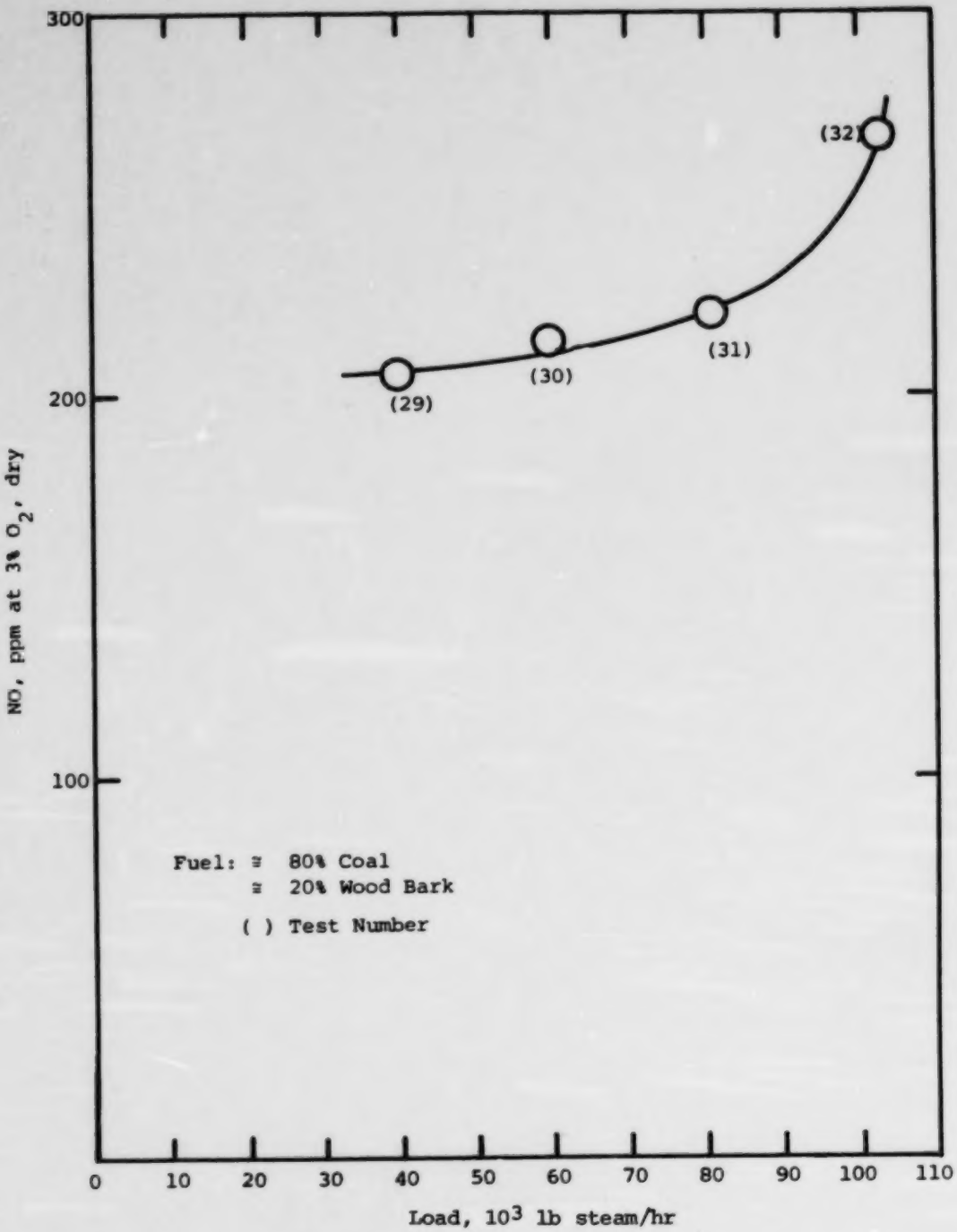

Figure 3-5. NO emissions as a function of load for a wood bark boiler.

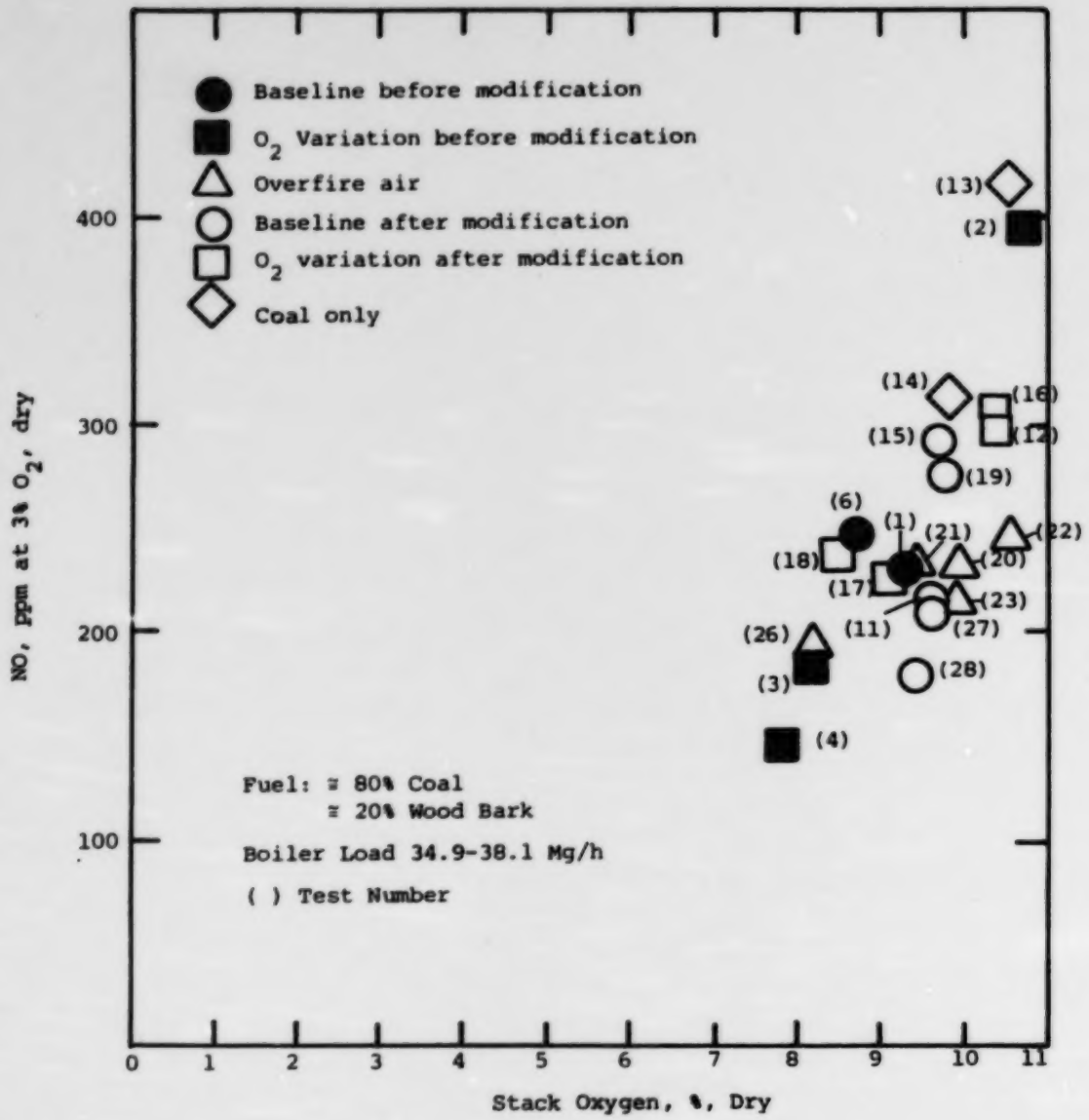

Figure 3-6. Location 3 -- NO emissions as a function of stack O_2 .

Total and solid particulate emissions were measured at the low NO_x condition described earlier. Solid particulate concentration was 118 ng/J (0.274 lb/10^6 Btu) with the unit operating at 8.2 percent stack O_2. NO emissions were 121 ng/J at this condition.

The low-NO_x cascade impactor test (Test 3-24) is shown in Figure 3-7. Particulate diameter as a function of cumulative proportion of impactor catch is plotted. About 27 percent of the particles are below 3 µm aerodynamic diameter. The geometric mean particle size and geometric dispersion coefficient are 6 µm and 1.099 µm, respectively. A comparison of the baseline (Figure 3-4) and low-NO_x results (Figure 3-7) indicates that the geometric mean particle size for baseline operation is approximately 50 percent of that measured during low-NO_x operation (3.2 µm vs. 6 µm). Closing the dampers for the overfire air and fly ash reinjection (low-NO_x configuration) resulted in the production of larger particulates, but at a reduced mass rate (118 ng/J vs. 155 ng/J).

A wet chemistry SO_x test (Test 3-25) resulted in 784 ng/J of SO_2 and 4 ng/J of SO_3.

The conclusions from these tests are that closing the dampers on both the overfire air and fly ash reinjection resulted in lower particulate emissions. Little change in NO emissions was found when compared with data obtained before the modification. Overfire air adjustment reduced CO emissions (i.e., more complete combustion) even at low excess air conditions. Reduced excess air firing reduced NO emissions and helped this unit's problem with high superheater metal temperatures.

3.4.1 Efficiency

Efficiency of the wood bark boiler was calculated using the heat loss method described in the ASME Power Test Code. The appropriate fuel analysis in Table 3-2 was used in the calculations. Stack gas losses were calculated from the flue gas analyses and radiation loss was estimated from the ABMA standard Radiation Loss Chart. The efficiency data for each test condition is

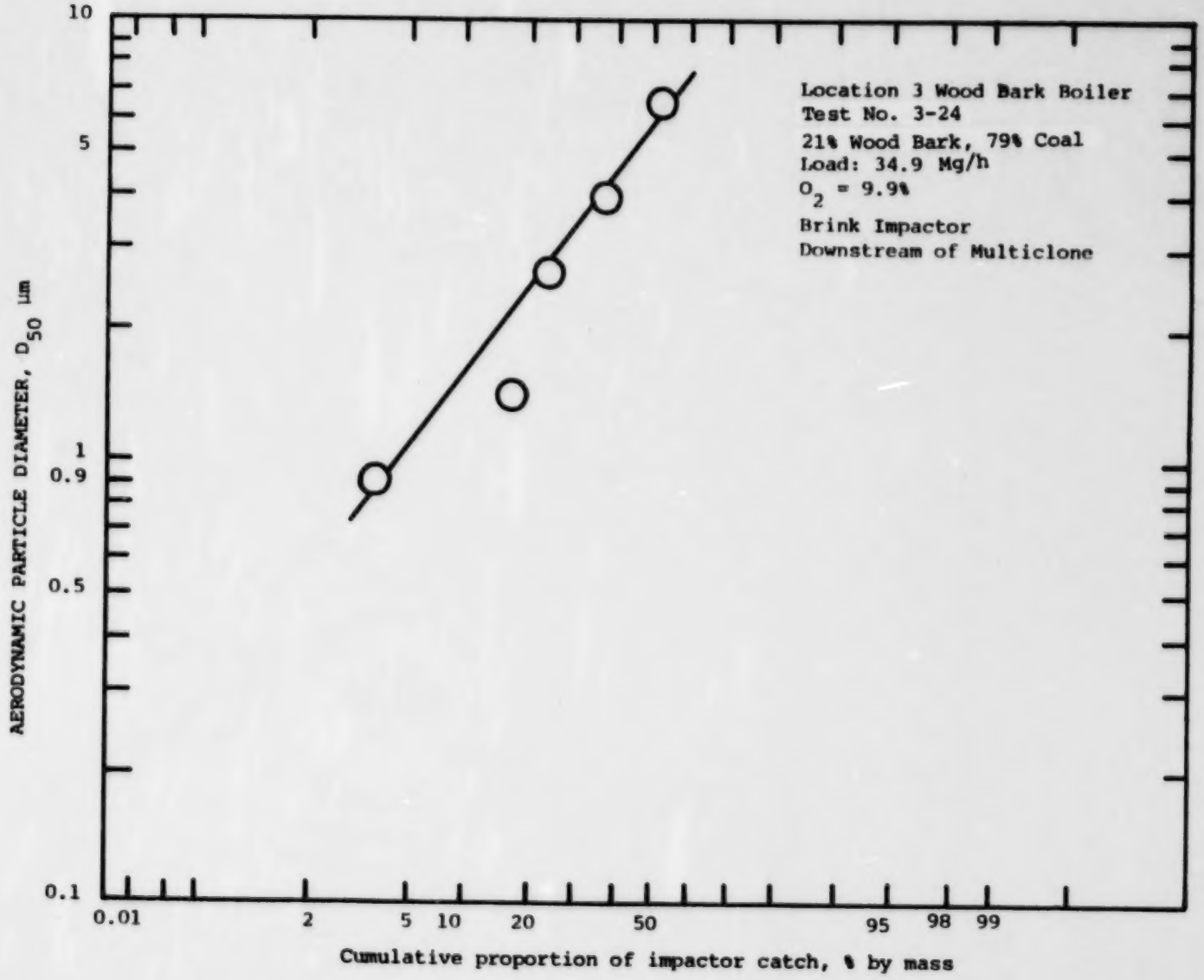

Figure 3-7. Aerodynamic Particle Diameter - Low-NO_x Conditions

presented in Table 3-1. Efficiency varied from 82.77 percent at 8.2 percent O_2 and a load of 82,000 lb/hr (37.2 Mg/h) steam flow to 76.86 percent at 10.6 percent O_2 and 78,000 lb/hr (35.4 Mg/h) steam flow. Low excess air firing resulted in improved efficiency without adversely affecting other operating conditions.

SECTION 4.0

HOGGED FUEL BOILER, LOCATION 5

4.1 BOILER DESCRIPTION

Full-scale combustion modification tests were carried out on a hogged fuel power boiler located at a large pulp and paper mill. The boiler is a spreader stoker rated at 58.6 MW thermal input (200,000 lb/hr steam flow -- 25.3 kg/s) when firing wood. Wood is the primary fuel and oil is used as a supplementary fuel only when the demand exceeds 58.6 MW (200,00 lb/hr -- 25.3 kg/s). The unit was placed into operation in September, 1977. The design specifications of the Combustion Engineering boiler are as follows:

1. CAPACITY - 200,000 lb/hr (58.6 MW)-wood only; 250,000 lb/hr (73.3 MW)-wood and oil
2. DESIGN PRESSURE - 700 psig (4,923 kPa)
3. OPERATING PRESSURE - 390 psig (2,785 kPa)
4. STEAM OUTLET TEMP - 600 deg. F (316 K)
5. STOKER - traveling grate (heating surface = 352 sq. ft. or 32.7 m^2)
6. OIL BURNERS - (4) at one elevation, oriented tangentially
7. IGNITORS - High energy arc (1) per burner
8. BOILER HEATING SURFACE 15,242 sq. ft. (1,416 m^2)
9. WATER WALL HEATING SURFACE 5,482 sq. ft. (509 m^2)

A schematic of the combustion air, flue gas, and wood handling systems is given in Figure 4-1. The hogged fuel was fed from the storage bin via conveyor belt to the screw feeders (large pieces of wood are recycled through the hogger where they are chopped and sent back through the system). The wood flow rate was controlled by the screw feeder RPM. The wood flow was determined volumetrically by integrating over the screw feeder revolutions. A strip chart in the control room displayed the mass flow rate of the wood fuel

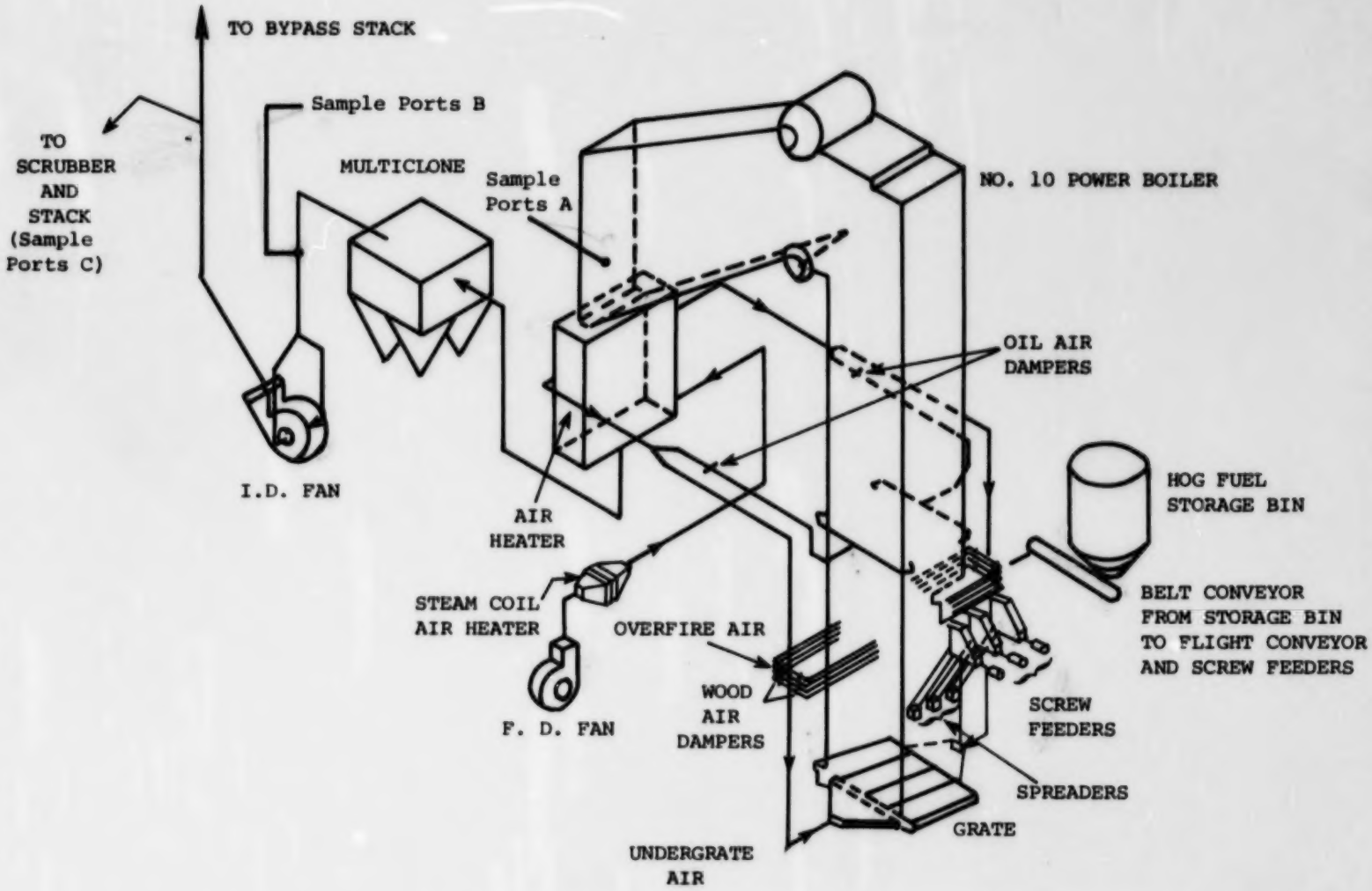

Figure 4-1. Flow diagram of combustion air and hogged fuel induction systems.

which was determined using an average density for the wood. The wood mass flow measurement was not very accurate because of varying densities. This fact was verified after the tests by calculating wood flows based on steam flow, actual fuel heating value (as determined by laboratory analysis), and efficiency data.

The balanced draft combustion air system consisted of an air heater, undergrate air system (four zones front to back), overfire air ports (four elevations each with four ports located in the corners and oriented tangentially), and an air system for the four oil guns (controlled by five dampers located near each gun).

The flue gas, after leaving the boiler proper, passed through the air heater making a right-angle bend at the air heater hoppers. From this point the flue gas passed through the multiclone and on through a venturi-type scrubber and out the stack. A bypass stack was used when the scrubber was off-line.

Most of the emissions sampling was done at the boiler outlet above the entrance to the air heaters (Ports A). Simultaneous particulate measurement was made at the multiclone outlet during one test (Ports B) and at the stack (Ports C) during another test to determine the particulate removal efficiency of different sections of the flue gas system.

4.2 FUEL DESCRIPTION

The hogged fuel consists of sawmill wastes purchased from neighboring mills. All hogged fuel arrives by barge. Bark and wood waste from fir and hemlock logs constitutes approximately 90 percent of the hogged fuel. Moisture content of this fuel can vary from 44 percent to 58 percent depending on source and season. Salt content of the fuel varies from 0.7 percent to 1.6 percent. The salt content of the hogged fuel is the result of storing or transporting logs in salt-containing waterways. Most of the hogged fuel is unloaded directly into an inside storage bin.

Three wood fuel analyses and two No. 6 oil analyses are presented in Table 4-1. Analyses of ash samples obtained during Test 5/2-1d are shown in

LOCATION 5 FUEL ANALYSES

TABLE 4-1. LOCATION 5 FUEL ANALYSES

Sample Identification:

1. Wood fuel sample Loc. 5, 9-20-79, Test 5/2-1b
2. Wood fuel sample Loc. 5, 10-3-79, Test 5/2-4a
3. Wood fuel sample Loc. 5, 10-17-79, Test 5/7-2
4. No. 6 Fuel Oil Loc. 5, 9-13-79, Test 5/1-1
5. No. 6 Fuel Oil Loc. 5, 10-23-79, Test 5/7-2C

Wood Fuel Samples:

Proximate Analysis:

	1	2	3	Avg.
Moisture, %	51.76	44.64	50.05	48.82
Volatile Matter, %	37.59	42.27	38.29	39.38
Ash, %	2.55	3.64	2.02	2.74
Fixed Carbon, %	8.10	9.45	9.64	9.06

Ultimate Analysis (Dry Basis):

	1	2	3	Avg.	Avg. Ash-Free
Carbon, %	47.13	48.53	49.81	48.49	51.20
Hydrogen, %	5.66	5.50	5.69	5.62	5.93
Nitrogen, %	0.16	0.21	0.27	0.21	0.22
Sulfur, %	0.11	0.088	0.091	0.10	0.11
Ash, %	5.29	6.57	4.04	5.30	-
Oxygen, % (by difference)	41.65	39.10	40.10	40.28	42.53
Heat of Combustion (Dry Basis):					
Gross Btu/lb (kJ/kg)	8207 (19090)	8438 (19626)	8674 (20175)	8440 (19630)	8912 (20728)

No. 6 Fuel Oils

Ultimate Analysis:

	4	5	Avg.
Carbon, %	89.21	89.69	89.45
Hydrogen, %	8.27	7.65	7.96
Nitrogen, %	0.45	0.39	0.42
Sulfur, %	1.52	1.71	1.62
Ash, %	0.019	0.030	0.02
Oxygen, % (by difference)	0.53	0.53	0.53
Heat of Combustion:			
Gross Btu/lb (kJ/kg)	17,550 (40703)	17,220 (40052)	17,385 (40435)
Net Btu/lb (kJ/kg)	16,800 (39075)	16,520 (38424)	16,660 (38749)

Table 4-2. The carbon content of both ash streams was included in the boiler efficiency calculations.

4.3 MODIFICATIONS AND TESTS PERFORMED

The combustion modifications performed at Location 5 were the following:

1. Excess air variation
2. Load variation
3. Overfire air variation
4. Auxiliary air damper adjustments
5. Combustion air preheat variation

Excess air variation was accomplished by adjusting the induced- and forced-draft fan dampers to increase or decrease combustion air flow while maintaining as constant a fuel flow as possible. Since the wood fuel composition was quite variable (it was not possible to control the fuel composition during the tests), some difficulties were encountered in achieving steady conditions. At times the fuel flow had to be adjusted to maintain the desired steam flow, thus, oxygen levels tended to fluctuate by plus or minus approximately one percentage point. The average oxygen was varied from 5.0 percent to 9.3 percent during these tests.

In the load variation series of tests, steam flow was varied from baseline (approximately 70-80 percent of full capacity) to 90 percent of capacity and then to approximately 50 percent of capacity. Two different oxygen conditions were set up at both the high and the low steam flow rates. In this test series and in other tests at Location 5, some load fluctuations occurred. This is partly because of variability of the wood fuel, but also because the boiler was designed as a load-following unit. The other boiler in the powerhouse at Location 5 is a black liquor recovery boiler. In operation, the recovery boiler is baseloaded and the hogged fuel boiler takes load swings. Although the plant was quite cooperative in maintaining constant load on the hogged fuel boiler during emissions tests, some unsteadiness was

TABLE 4-2. LOCATION 5 ASH ANALYSES

Test 5/2-1d

Bottom Ash

	As Received	Dry Basis
Moisture, %	0.88	0
Ash, %	93.94	94.77
Sulfur, %	0.16	0.16
Carbon, %	3.85	3.88
Heat of Combustion (gross and net):		
Btu/lb	331	334
kJ/kg	770	777

Fly Ash

	As Received	Dry Basis
Moisture, %	4.71	0
Ash, %	44.88	47.10
Sulfur, %	0.27	0.28
Carbon, %	47.37	49.71
Heat of Combustion (gross and net):		
Btu/lb	7,047	7,395
kJ/kg	16,390	17,200

unavoidable. In general, load could be held to within about ±5 percent of some average value over the course of the day's tests, however, over several days the load variations were on the order of ±15 percent and more for a few tests. In some cases, No. 6 oil had to be burned in order to keep the fire steady and to maintain load.

Three values of overfire air (OFA) were evaluated: a baseline value of 5.7 percent of total combustion air, a high of 9.7 percent, followed by zero OFA. As shown in Figure 4-1, there were four elevations of overfire air, each with four tangentially-oriented ports. At baseline conditions only the fourth elevation (highest above grate) was used. At the high overfire air condition the top two elevations were used.

The overfire air elevations were either on or off; no throttling of the flow was possible. The lowest two elevations of overfire air are not used by the plant because it was determined soon after the boiler installation that stack opacity increased when they were used and efficiency was decreased. In addition, when more than two elevations of overfire air were used, grate temperatures became dangerously high due to the reduced undergrate air flow.

The auxiliary air dampers are part of the oil air system shown in Figure 4-1. They are located near each of the four oil guns which are mounted in the four corners above the overfire air ports. There are five air registers for each of the oil guns. In the baseline condition when no oil was fired there was no air flow through these registers. In the modified condition the lowest of the five registers (auxiliary air damper "AA") was opened 10 percent and air was thus injected at approximately the level of the oil guns without any oil flow. Thus, the adjustment provided an alternative to overfire air as a means of staged combustion air. The other oil air registers were also adjusted but did not appear to give NO_x emissions as low as the auxiliary air damper "AA" adjustment.

The combustion air temperature was varied from baseline level to a low inlet air temperature by bypassing the steam coil portion of the air heater for that particular test. The combustion air temperature dropped from 517°F

(543 K) to 477°F (521 K) at high load and from 495°F (531 K) to 467°F (515 K) at baseline load. Thus, only modest changes in combustion air temperature were achievable.

A complete set of emissions measurements including gaseous, total and solid particulate and particulate size, wet chemical SO_x, and polycyclic organic matter (POM) was made for the baseline condition. The same series of tests (except for wet chemical SO_x measurement) was run at the optimum low NO_x conditions which was a combination of low excess air and auxiliary air damper adjustment. Nearly complete sets of gaseous O_2, CO, CO_2, NO, NO_x, SO_2, and HC emissions were obtained on all tests. Appendix A provides a description of the measurement equipment.

4.3.1 Results

The data from Location 5 is summarized in Tables 4-3 and 4-4. The particulate measurements in Table 4-3 were obtained at the boiler outlet (upstream of multiclone) while those in Table 4-4 were obtained downstream of multiclone. The data yields two important observations:

1. NO_x emissions were low with only a single reported concentration over 100 ppm.

2. Particulate emissions prior to any dust collecting device were high and variable. The range of total particulate concentrations measured at the boiler outlet was 1270 - 3780 ng/J (2.96 - 8.79 lb/10^6 Btu). The overall fly ash removal efficiency based on one set of simultaneous particulate measurements at the boiler outlet and at the stack was 84 percent.

The average NO emissions for the baseline and optimum low NO_x configurations are shown in Table 4-5. The average reduction in NO concentration based on those values is 17.2 percent.

Boiler efficiency increased at the low NO_x conditions to 72.3 percent (average for Tests 5/5-2, 5/7-2b, and 5/7-2c) from the baseline efficiency of 71.1 percent (average for Tests 5/5-1, 5/7-1b, and 5/7-1c) for a gain of 1.7 percent. The auxiliary air damper "AA" adjustment thus gave reduced NO_x emissions and the maximum efficiency condition at baseline load.

TABLE 4-3. SUMMARY OF GASEOUS AND PARTICULATE EMISSIONS, LOCATION 5 - HOGGED FUEL BOILER

Test No.	Date 1979	Steam Flow Kg/s	Steam Flow 10^3 lb/hr	Heat Input Rate MW	Heat Input Rate 10^6 Btu/hr	O_2 %	CO_2 %	NO_x ppm*	NO_x ng/J†	NO ppm*	NO ng/J†	HC ppm*	HC ng/J	CO ppm*	CO ng/J	SO_2 ppm*	SO_2 ng/J
S/1-1	9-17	28.0	222	78.0	266	8.3	12.7	103	56	97	53	81	15	929	306	44	33
S/2-1a	9-21	19.3	153	53.9	184	7.2	12.0	80	43	74	40	47	9	1522	502	13	10
S/2-1b	9-20	16.6	132	46.3	158	8.7	10.0	81	44	72	39	213	40	>2656	>875	30	23
S/2-1c	9-24	14.4	114	40.2	137	9.6	9.0	86	47	72	39	557	105	>3144	>1036	20	15
S/2-1d	9-25	20.0	159	56.0	191	6.9	12.4	50	27	48	26	91	17	>2585	>852	42	32
S/2-1e	9-26	17.6	140	49.2	168	7.1	13.6	45	24	43	23	44	8	>2258	>744	97	73
S/2-1f	10-1	21.0	167	58.6	200	5.4	14.5	59	32	55	30	139	26	>2312	>762	3	2
S/2-2	9-21	19.3	153	53.9	184	6.5	13.6	106	57	101	55	35	7	894	295	0	0
S/2-3	9-21	19.3	153	53.9	184	9.3	10.2	88	48	82	44	204	38	>3077	>1014	0	0
S/2-4	9-21	19.3	153	53.9	184	5.7	12.9	69	37	65	35	96	18	847	279	3	2
S/2-4a	10-3	20.2	160	56.3	192	5.0	15.0	69	37	68	37	130	24	2172	716	39	29
S/3-1	10-4	17.5	139	48.9	167	7.4	12.6	61	33	61	33	40	8	2310	761	8	6
S/3-2	10-4	22.7	180	63.3	216	4.8	15.9	49	27	49	27	112	21	>2222	>732	0	0
S/3-2a	10-4	22.7	180	63.3	216	7.7	12.4	53	29	53	29	141	27	>2707	>892	0	0
S/3-3	10-4	13.5	107	37.5	128	10.3	8.9	72	39	72	39	315	59	>3364	>1109	0	0
S/3-3a	10-4	13.5	107	37.5	128	7.0	12.9	53	29	51	28	72	14	>2571	>847	0	0
S/4-1	10-1	19.5	155	54.5	186	7.3	12.8	85	46	85	46	-	-	1130	372	0	0
S/4-2	10-1	19.5	155	54.5	186	8.1	10.3	67	36	67	36	223	42	865	285	0	0
S/4-3	10-1	19.5	155	54.5	186	7.4	11.7	57	31	53	29	214	40	1853	611	0	0
S/4-4	10-1	19.5	155	54.5	186	8.1	11.0	58	31	56	30	89	17	1298	428	0	0
S/4-2a	10-2	19.2	152	53.3	182	7.7	12.3	67	36	65	35	89	17	1780	587	47	35
S/5-1	10-16	18.1	144	50.7	173	8.3	11.8	89	48	85	46	60	11	1312	432	-	-
S/5-2	10-16	18.1	144	50.7	173	5.8	14.8	62	34	61	33	48	9	>2153	>710	-	-
S/5-3	10-16	18.1	144	50.7	173	7.4	12.8	81	44	78	42	68	13	2038	672	-	-
S/6-1	10-15	26.2	208	73.3	250	6.5	10.9	86	47	83	45	79	15	1460	481	-	-
S/6-2	10-15	23.6	187	65.6	224	7.1	9.9	99	54	96	52	50	9	700	231	-	-
S/6-1a	10-15	21.4	170	65.6	204	7.4	12.1	89	48	84	45	36	7	1055	348	-	-
S/6-2a	10-15	20.4	162	56.9	194	8.0	12.9	85	46	83	45	45	8	670	221	-	-
S/7-1	10-17	18.8	149	52.5	179	6.9	13.5	82	44	78	42	57	11	-	-	-	-
S/7-2	10-17	18.8	149	52.5	179	5.1	15.8	61	33	56	30	50	9	-	-	-	-
S/7-1a	10-18	18.9	150	52.8	180	8.1	10.6	76	41	73	40	-	-	-	-	-	-
S/7-2a	10-18	18.9	150	52.8	180	5.1	16.2	55	30	51	28	-	-	-	-	-	-
S/7-1b	10-22	17.6	140	49.2	168	8.7	10.6	61	33	59	32	-	-	>1463	>482	-	-
S/7-2b	10-22	17.6	140	49.2	168	5.6	14.4	54	29	54	29	-	-	>1165	>384	-	-
S/7-1c	10-23	18.0	143	50.4	172	7.6	12.3	66	36	62	34	103	19	1988	655	-	-
S/7-2c	10-23	18.0	143	50.4	172	6.2	13.9	65	35	59	32	92	17	2422	798	-	-

TABLE 4-3. (CONTINUED)

Test No.	Fuel Mix Wood/Oil % of heat in	Total Particulate (Blr.Out.) lb/10^6 Btu	Total Particulate (Blr.Out.) ng/J	Solid Particulate (Blr.Out.) lb/10^6 Btu	Solid Particulate (Blr.Out.) ng/J	Air Heater Gas Out Temperature °F	Air Heater Gas Out Temperature K	Boiler Eff. %	Comments
S/1-1	75/25	0.50	3660	0.37	3660	463	513	79.2	As Found
S/2-1a	100/0	-	-	-	-	465	514	68.6	Baseline
S/2-1b	100/0	5.12	2200	5.07	2180	455	508	67.5	Baseline-Brink
S/2-1c	80/20	7.41	3190	7.27	3120	441	500	75.6	Baseline-Multiclone efficiency-bad wood
S/2-1d	100/0	-	-	-	-	471	517	68.8	Baseline-Brink and SO_x-bad wood
S/2-1e	100/0	2.96	1270	2.87	1240	460	511	69.8	Baseline-POM-bad wood
S/2-1f	100/0	-	-	-	-	453	507	70.5	Baseline-Brink
S/2-2	100/0	-	-	-	-	465	514	69.6	Low O_2-unsteady conditions
S/2-3	100/0	-	-	-	-	470	516	67.1	High O_2
S/2-4	100/0	-	-	-	-	470	516	69.0	Minimum O_2
S/2-4a	100/0	8.79	3780	8.77	3770	462	512	70.4	Minimum O_2-Brink
S/3-1	100/0	-	-	-	-	465	514	69.1	Baseline
S/3-2	100/0	-	-	-	-	480	522	70.3	High Load-Low O_2
S/3-2a	100/0	-	-	-	-	460	511	69.2	High Load-High O_2
S/3-3	100/0	-	-	-	-	420	489	67.7	Low Load-High O_2
S/3-3a	100/0	-	-	-	-	440	500	69.8	Low Load-Low O_2
S/4-1	100/0	-	-	-	-	465	514	69.1	Baseline
S/4-2	100/0	-	-	-	-	440	500	68.2	High OFA
S/4-3	100/0	-	-	-	-	455	508	68.8	Zero OFA
S/4-4	100/0	-	-	-	-	445	503	68.6	Repeat Baseline
S/4-2a	100/0	3.82	1640	3.81	1640	454	508	69.2	High OFA
S/5-1	100/0	-	-	-	-	428	493	69.8	Baseline
S/5-2	100/0	-	-	-	-	433	496	71.2	Aux.Air "AA" dpr. adj.
S/5-3	100/0	-	-	-	-	430	494	70.4	Oil Air "C" adj.
S/6-1	85/15	-	-	-	-	454	508	75.6	High Load
S/6-2	85/15	-	-	-	-	405	480	73.0	Low C.A. Temp.-High load
S/6-1a	100/0	-	-	-	-	394	474	67.6	Low C.A. Temp.
S/6-2a	100/0	-	-	-	-	440	500	70.0	Baseline
S/7-1	100/0	-	-	-	-	450	505	-	Baseline
S/7-2	100/0	5.64	2430	5.62	2420	440	500	-	Low NO_x-Brink
S/7-1a	100/0	-	-	-	-	440	500	-	Baseline
S/7-2a	100/0	3.50	1505	3.48	1500	440	500	-	Low NO_x-Brink-POM
S/7-1b	100/0	-	-	-	-	430	494	68.9	Baseline
S/7-2b	100/0	-	-	-	-	453	507	70.4	Low NO_x-Brink
S/7-1c	91/9	-	-	-	-	440	500	74.7	Baseline
S/7-2c	91/9	5.83	2510	5.82	2500	443	501	75.4	Low NO_x-Total partic.removal efficiency

* dry, corrected to 3% O_2, dry

† as NO_2

TABLE 4-4. ADDITIONAL EMISSIONS DATA, LOCATION 5

Test No. (Location)	Date, 1979	Steam Flow kg/s	Steam Flow 10^3 lb/hr	O_2, % dry	Wet Chemical SO_2 ppm*	Wet Chemical SO_2 ng/J	Total Particulate lb/10^6 Btu	Total Particulate ng/J	Solid Particulate lb/10^6 Btu	Solid Particulate ng/J	Particulate Removal Efficiency Percent	Comments
5/2 - 1c (Multiclone Outlet)	9-24	14.4	114	9.6	--	--	3.02	1300	2.85	1230	59.2	Multiclone efficiency only-multiclone partially plugged
5/7 - 2c (Stack)	10-23	18.0	143	9.0	--	--	0.92	394	0.88	377	84.2	Total particulate collection efficiency
5/2 - 1d (Boiler Outlet)	9-25	20.0	159	7.0	18	13.5	--	--	--	--	--	Zero detectable SO_3 - Goksoyr-Ross method

*Dry, corrected to 3% O_2

TABLE 4-5. EMISSIONS OF NO AT BASELINE AND OPTIMUM LOW-NO_x CONDITIONS

Condition	Mean, Standard Deviation ppm*	Mean, Standard Deviation ng/J†	No. of Data Pts.
Baseline	67.9, 13.5	36.8, 7.3	14
Low NO_x (aux. air dpr. "AA" adjustment)	56.2, 4.0	30.4, 2.0	5

*dry, at 3 percent O_2

†NO as NO_2

The particulate emissions at the optimum low NO_x condition ranged from 1500 - 2420 ng/J (3.50 - 5.83 lb/10^6 Btu). It was assessed that this emission level was not different from that found at baseline, which was 1270 - 3190 ng/J (2.96 - 7.41 lb/10^6 Btu).

However, when all of the total particulate data from all of the tests conducted upstream of the multiclone are plotted as a function of NO emissions, as is done in Figure 4-2, a trend of lower particulate emissions with lower NO emissions is noted. The reason for this behavior is unclear at present. Correlations were made of particulate emission with excess air level and with the pressure drop across the grate, however, no meaningful result was obtained with either variable. The wood fuel composition and the size of the wood fuel may be the most important variables affecting the particulate emissions from the hogged fuel boiler, and may influence NO_x emissions as well.

The Brink cascade impactor tests conducted at the boiler outlet were analyzed to determine if the solid particulate size distribution was related

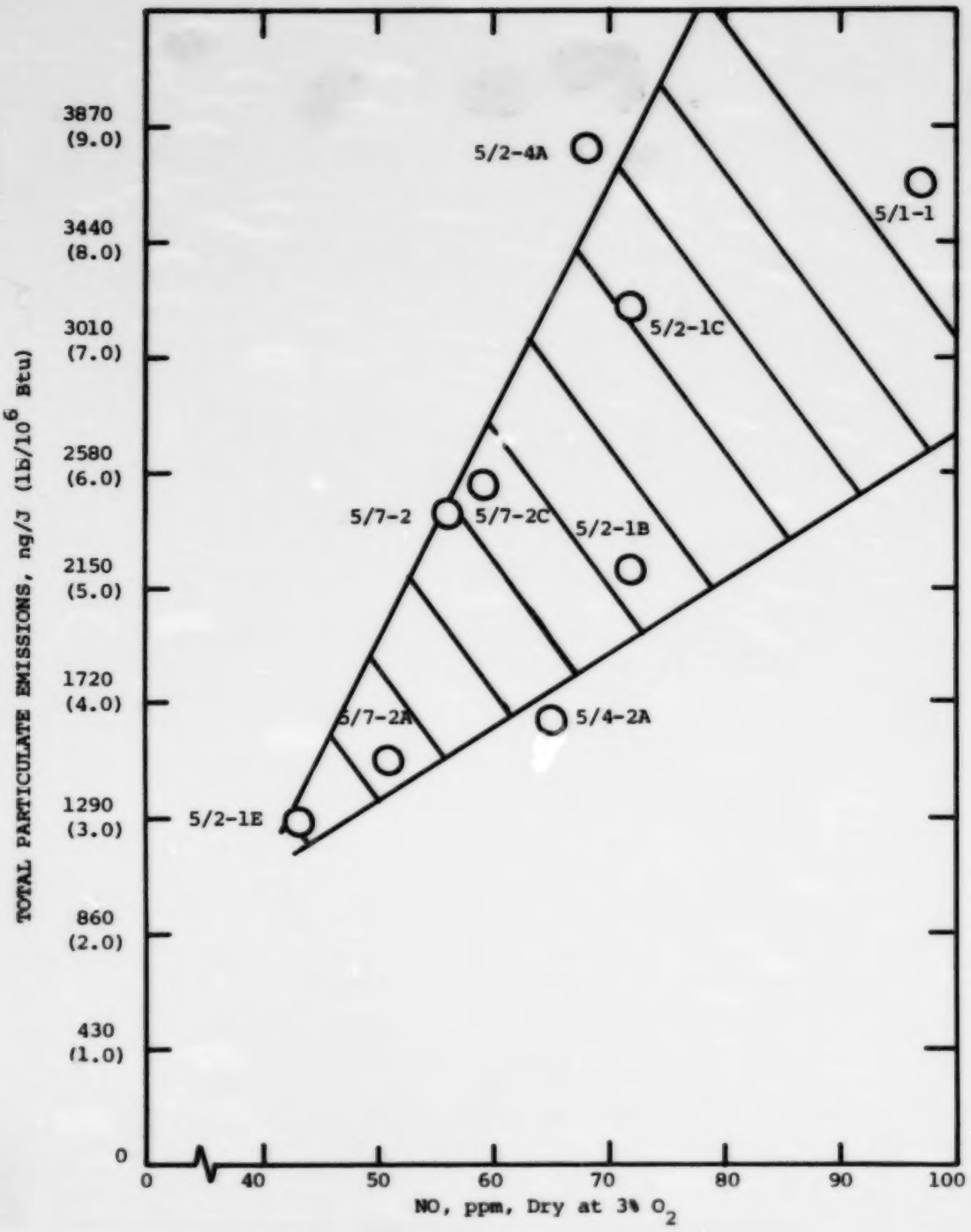

Figure 4-2. Boiler total particulate emissions as a function of NO emissions for various test conditions on a hogged fuel boiler.

to boiler operation. (Three of these distributions are shown in Figures 4-3 through 4-5.) These distributions, characterized by their mass median particle size, are summarized below:

Test No.	Operating Condition	Median D μm	Emission Factor lb/10^6 Btu	Emission Factor ng/J
5/2-4a	Minimum O_2	200	8.77	3770
5/7-2b	Low NO_x	250	6.92	2980
5/2-1f	Baseline	600	5.79	2490
5/7-2	Low NO_x	38	5.62	2420
5/2-1b	Baseline	250	5.07	2180
5/7-2a	Low NO_x	22	3.48	1500

These data indicate that there was no clear relationship between the mass median diameter and either the particulate emission factor or the boiler operating condition. (As will be discussed shortly, there is a relationship between the particulate temperature factor and wood ash content.)

Although the size of the fuel was not characterized, it is anticipated that for fuels of equal ash content, smaller pieces of fuel would be more easily entrained in the flue gas after combustion and would lead to larger particulate concentrations having smaller aerodynamic particle diameters. Larger pieces of fuel would tend to burn on the grate and fall into the ash pit after combustion and less fine material would be carried out of the boiler in the flue gas. The boiler did not have the instrumentation necessary to separately measure the amount, if any, of sander dust or wood shavings used during a test.

While the total impactor catch weight was considerable, much of the particulate material was large and, therefore, was caught in the precutter cyclone before reaching the stages. Figures 4-3 through 4-5 show that only 20 - 40 percent of the total catch actually impacted on the stages. During some of the tests the impactor jets became plugged and sampling had to be discontinued prematurely. Thus, the sample weight on the stages was sometimes less than ideal.

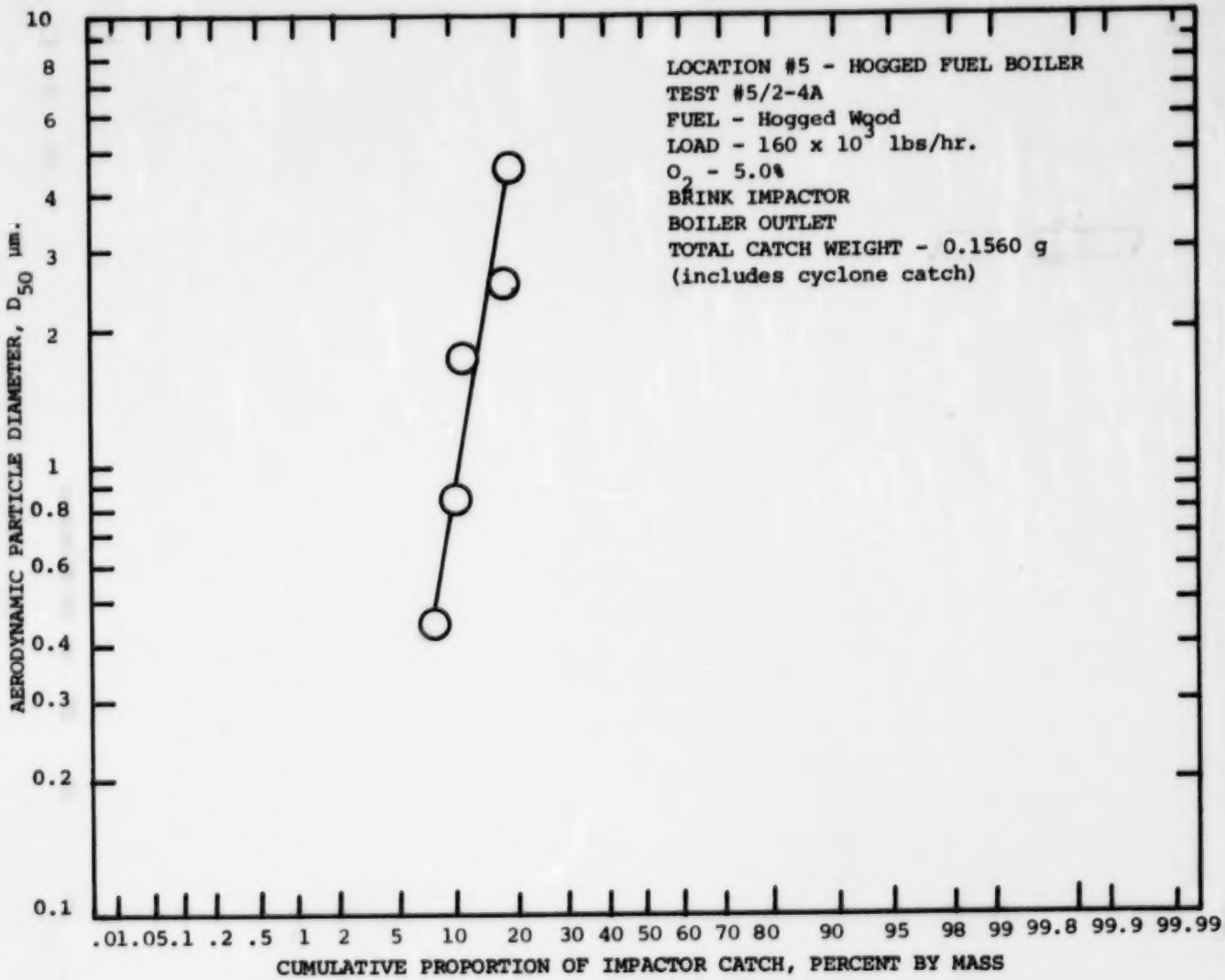

Figure 4-3. Aerodynamic particle diameter as a function of cumulative proportion of impactor catch at low-O_2 conditions in a hogged fuel boiler.

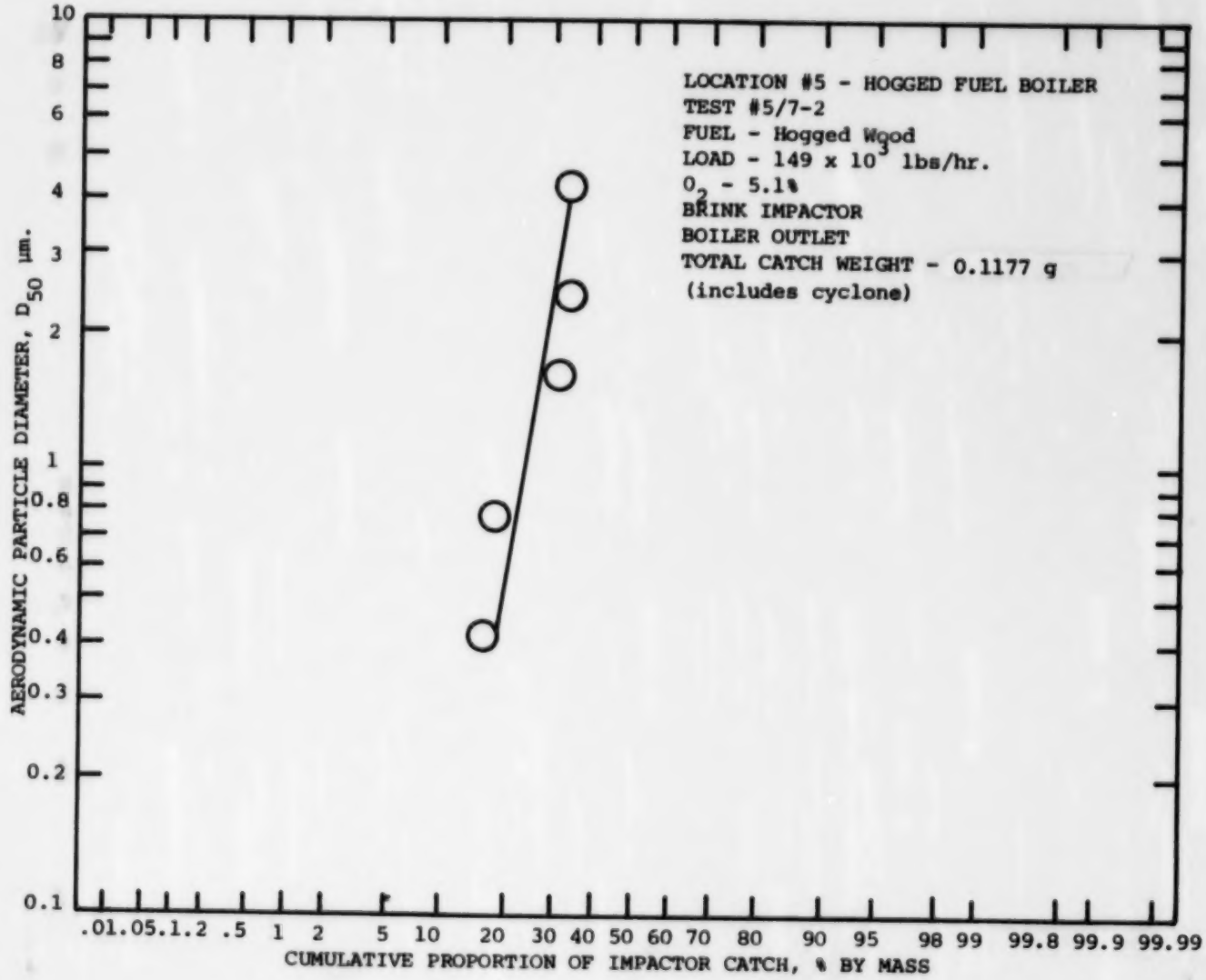

Figure 4-4. Aerodynamic particle diameter as a function of cumulative proportion of impactor catch at low NO_x conditions in a hogged fuel boiler.

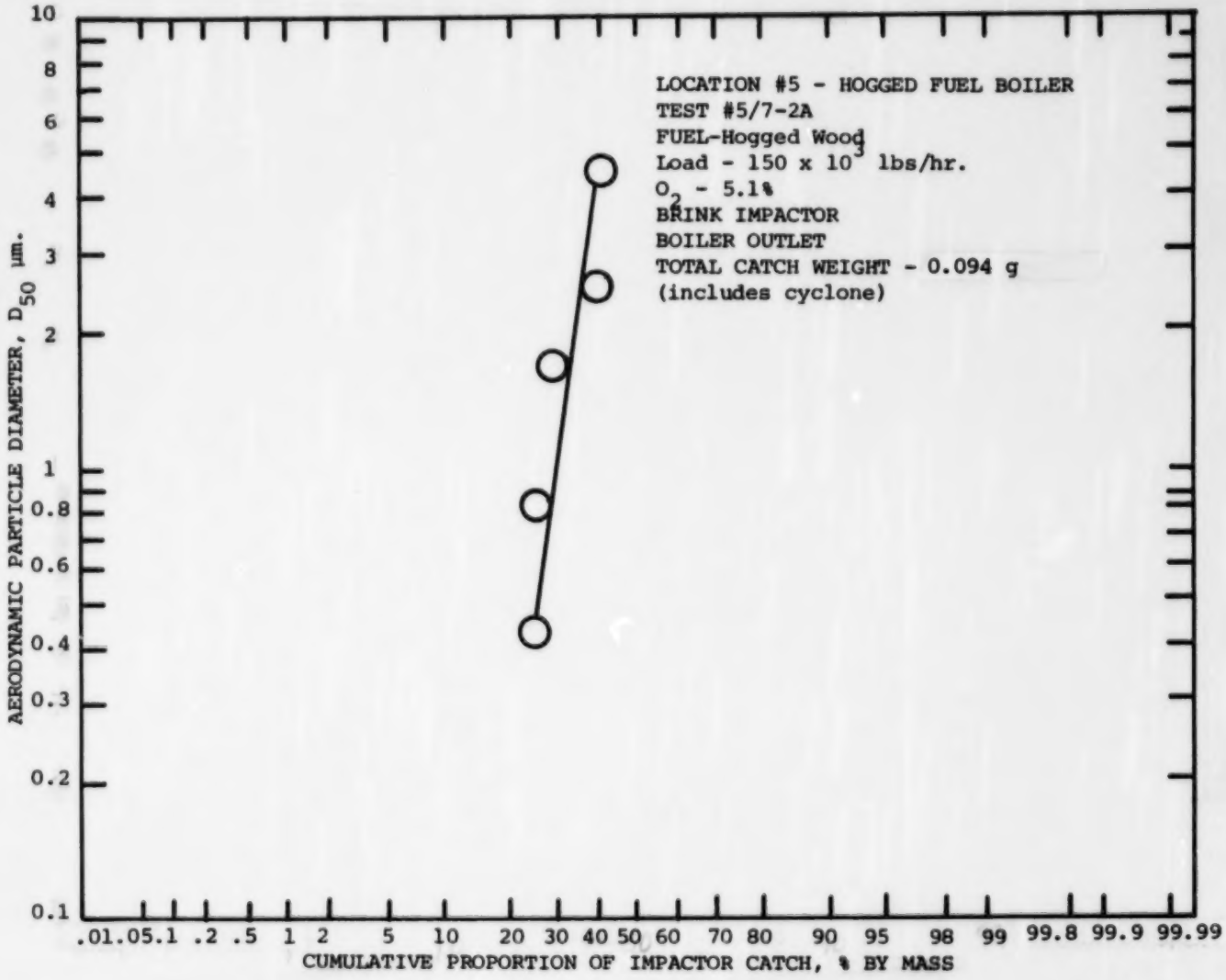

Figure 4-5. Aerodynamic particle diameter as a function of cumulative proportion of impactor catch at low NO_x conditions in a hogged fuel boiler.

The fuel composition data obtained show that there is some correlation of total particulate emission with the ash content of the wood fuel. This correlation is shown in Figure 4-6. Since a large portion of the fuel ash (probably over 70 percent) is fly ash rather than bottom ash one would expect such a correlation. Because of the spread in the data it was not possible to separate the effects of different operating conditions on emissions. Thus, the curve shown is an overall curve not specific to only one set of conditions. The curve in Figure 4-6 was fit by linear least square regression analysis. A correlation coefficient approaching unity indicates a good fit and a coefficient approaching zero indicates a poor fit. As noted, the correlation in terms of wood ash content can explain 68.9 percent of the variation in total particulate.

To determine whether or not there was a relationship between the moisture content of the fuel and total particulate emission, the data were plotted and a linear regression analysis performed. The result was a correlation coefficient of only 10.1 percent indicating a weak relationship between particulate emission and wood moisture content. The data indicates that, under different boiler operating conditions, total particulate can vary by as much as a factor of three for nearly the same fuel moisture content. Although it is reasonable to suppose that the amount of moisture in the fuel affects the burnout of the wood pieces, other factors appear to play a more significant role in the combustion and carryover of the wood. More data would be required at the various operating conditions to determine their true effects on particualte emission.

Figure 4-7 was generated by linear regression of the NO emission versus fuel moisture data. A somewhat better correlation was found (r^2 = 26.3 percent), however, there is still a large amount of data scatter. Based on previous tests of steam and water injection in boilers, it might be expected that increased moisture content of the fuel would result in lowered flame temperatures and reduced NO emission, however, this does not appear to be the case for the hogged fuel boiler at Location 5.

In a similar manner, NO emission was evaluated as a function of fuel nitrogen in an attempt to determine whether or not any correlation existed.

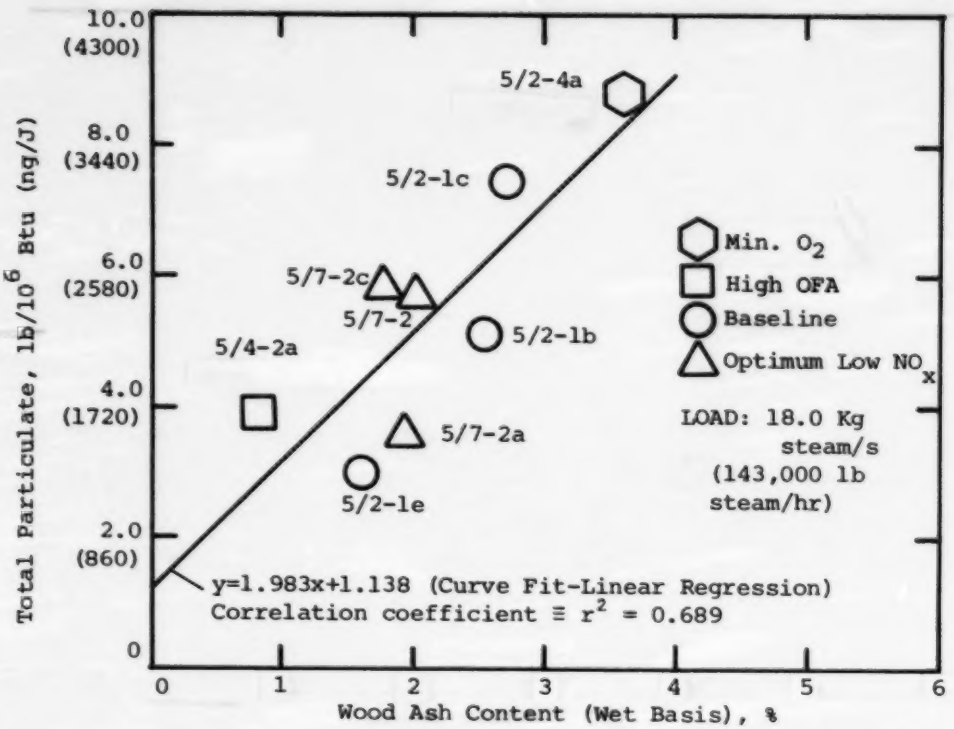

Figure 4-6. Total particulate as a function of wood ash content for a hogged fuel boiler.

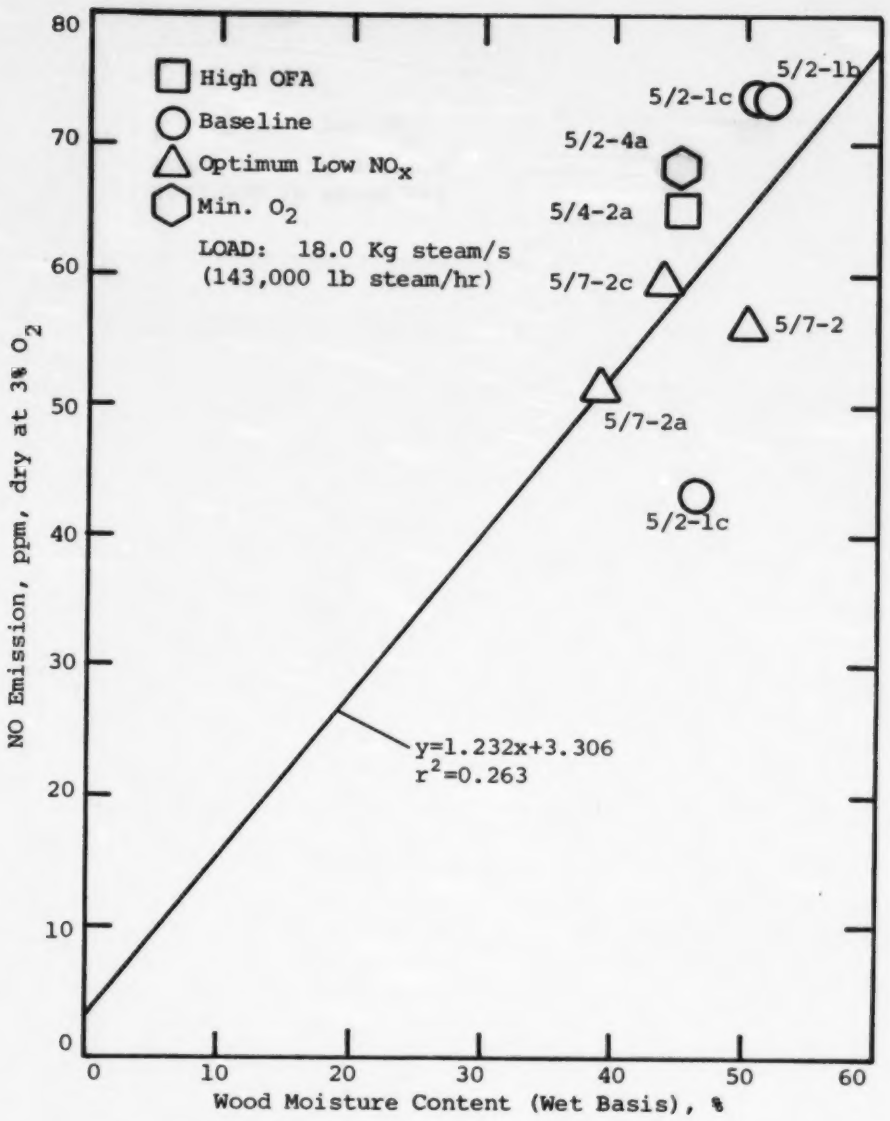

Figure 4-7. NO emission as a function of wood moisture content for a hogged fuel boiler.

The data were too scattered to develop a meaningful curve. However, the data indicate that there was no significant increase in NO emission as fuel nitrogen increased. (The weight percent of nitrogen in the fuel varied over a narrow range from 0.08 percent to 0.14 percent on a wet basis.)

Very low SO_2 emissions were measured either by wet chemical technique or continuous gaseous analyzer. The SO_2 emission data were presented in Table 4-2. There are two reasons for the low SO_2 emission:

1. Low fuel sulfur content (0.09 - 0.11 percent by weight on a dry basis).

2. Ash sulfur retention. Analysis of the fly ash and bottom ash yielded sulfur values (dry basis) of 0.28 percent and 0.16 percent, respectively. These values exceeded that for the wood fuel indicating some degree of sulfur concentration in these ash streams.

Changing fuel sulfur content and, no doubt, sulfur content of the fly ash and bottom ash (sulfur in the fly ash and bottom ash was measured for only one test) caused some variation in SO_2 emission, however, the absolute level of SO_2 was generally less than 50 ppm, dry at 3 percent O_2. The error in the continuous analyzer SO_2 data at this low level for these tests approached 20 - 30 percent due to problems with the analyzer.

Gaseous SO_2 measurement was made for the first twenty-one tests with the DuPont 400 Photometric Analyzer. A wet chemical SO_x test (Goksoyr-Ross method) yielded 18 ppm (13.5 ng/J) of SO_2 and no detectable SO_3. By comparison, the DuPont analyzer indicated 42 ppm of SO_2 during the same test. The DuPont analyzer was down for repair during the remainder of the test program at Location 5.

The results of the excess air variation test series at three different boiler loads are shown in Figure 4-8. The maximum NO reduction obtained by reducing the excess air from baseline (7.2 percent oxygen) to 5.7 percent oxygen was 12 percent. The efficiency at the reduced excess air condition was slightly higher than that at baseline condition. CO emissions were also reduced in two of the three lowered excess air tests.

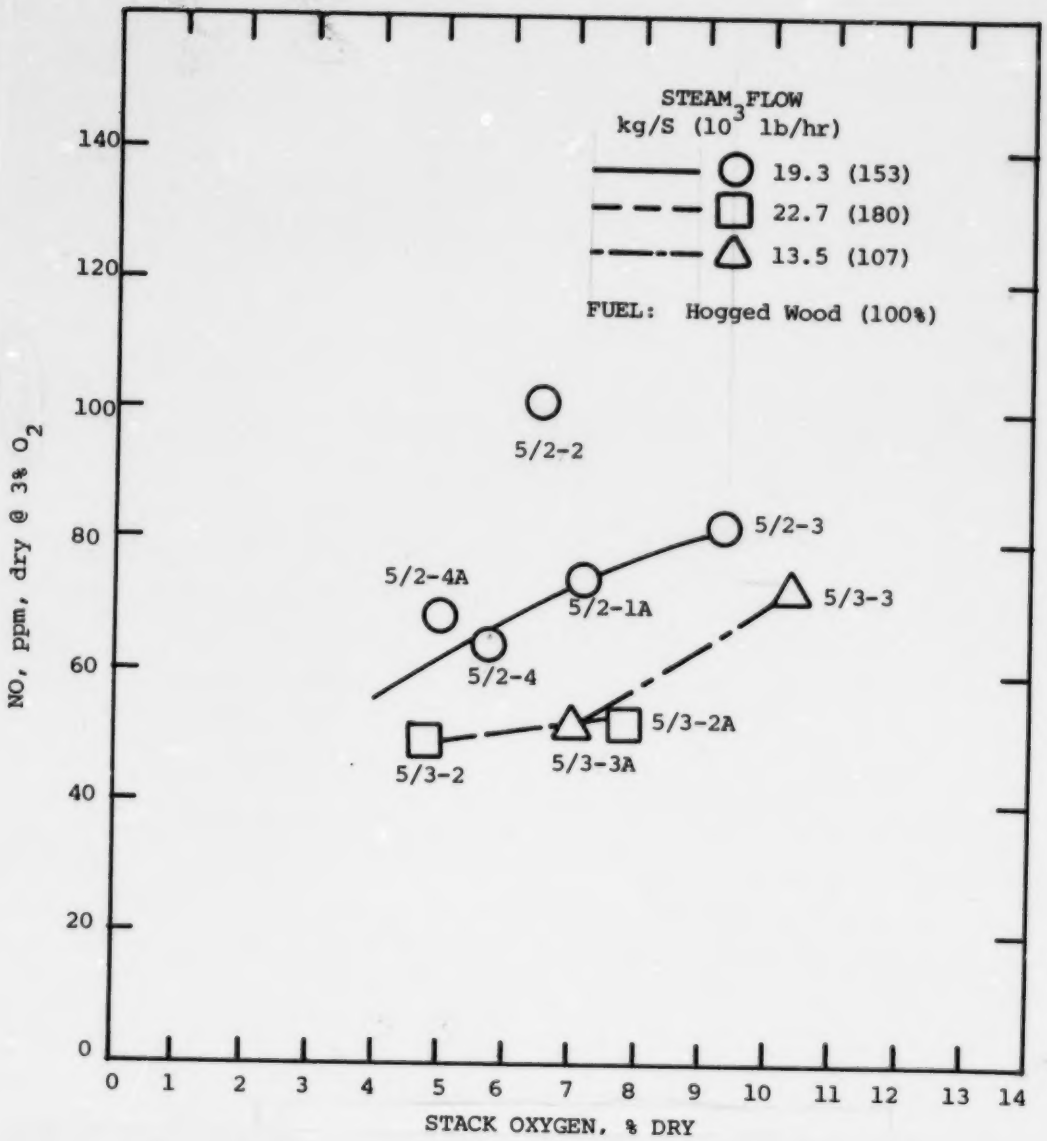

Figure 4-8. NO emissions as a function of stack oxygen for three loads in a hogged fuel boiler.

Similar behavior of NO_x emission versus excess oxygen was found to occur at full capacity and half capacity. NO emissions at both high and low loads were less than emissions at baseline by approximately 30 percent. CO emissions, however, were high for both full and half capacity tests. Unburned hydrocarbons (as methane) are reported in Table 4-3; however, the data appear to be quite variable.

NO_x emissions were reduced by increasing the overfire air in another series of modification tests. The reduction in emissions from baseline was 21 percent (from 85 ppm to 67 ppm) and CO emissions were reduced at the same time from a baseline level of 1130 ppm to 865 ppm. However, the efficiency was reduced by 1.3 percent at the high overfire air condition. These calculations are made by comparing the baseline value from test 5/4-1 to the high overfire air test 5/4-2. (Test 5/4-2a was also conducted at high overfire air conditions, but was done on a different day.)

Shutting off the overfire air produced no significant change in NO emissions as is seen by comparing the emissions from test 5/4-3 to those of 5/4-4, however, CO emission increased considerably at zero overfire air. No definite relationship of particulate emissions with overfire air variation can be determined from the data.

Lowering the combustion air temperature by only a modest amount had little impact on NO_x emissions, but increased CO emissions. The effect of the optimum low NO_x register adjustment (10 percent open auxiliary damper "AA", others closed) on NO_x emissions is shown in Table 4-4. The effect of this modification on efficiency has already been discussed. Other oil air registers were adjusted but failed to achieve the same NO_x reduction.

The effect of the auxiliary air damper "AA" adjustment coupled with lowered excess air on NO emissions is shown in Figure 4-9.

4.4 POLYCYCLIC ORGANIC MATTER (POM) SAMPLING

POM sampling was conducted at Location 5 for baseline conditions and for the optimum low NO_x condition with the boiler operating at 70 - 75 percent of capacity. One POM test, at the boiler outlet, was run at each condition.

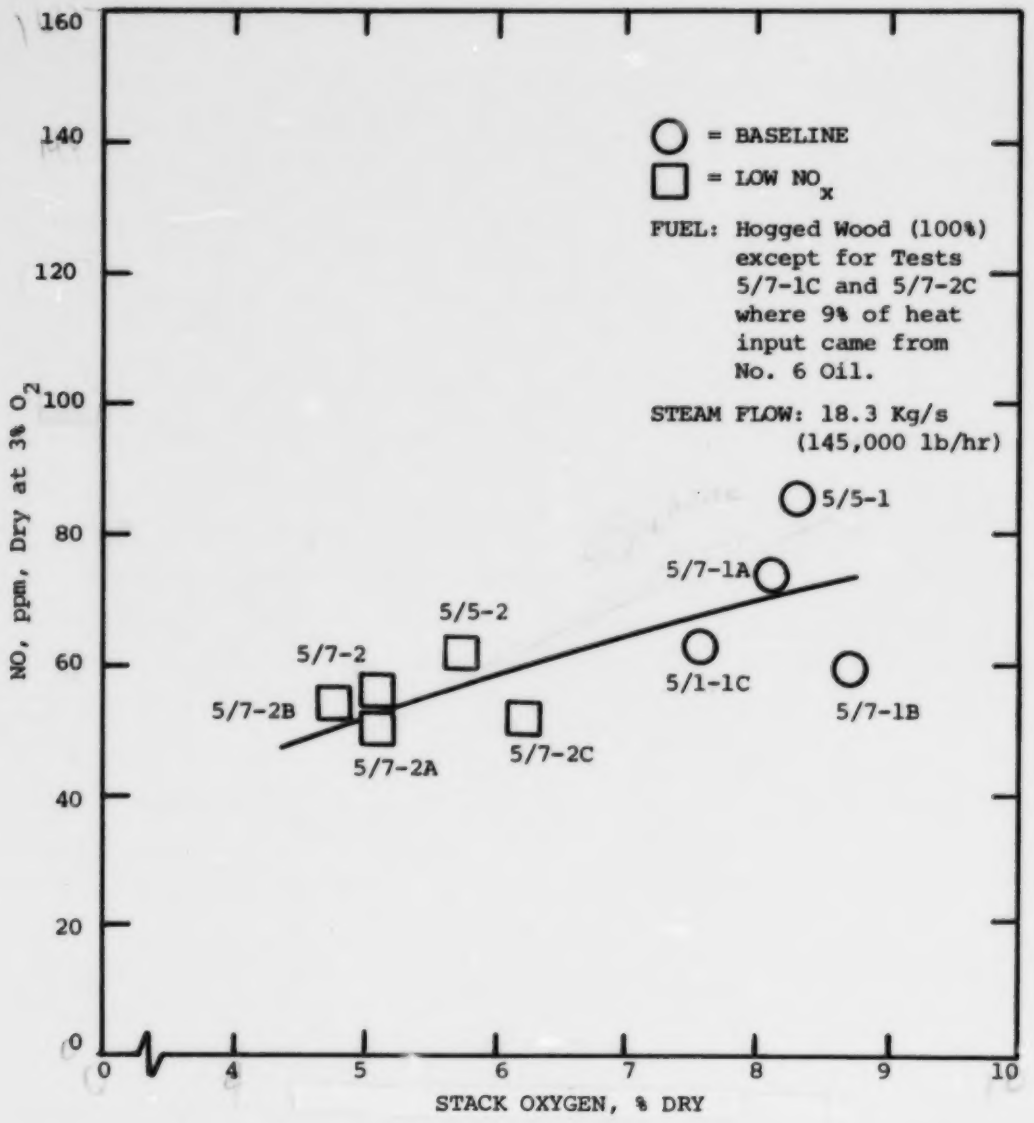

Figure 4-9. NO emission as a function of stack oxygen in the baseline and low-NO_x configurations.

The sampling system is a modified Method 5 sampling train developed by Battelle Columbus Laboratories. A combination of conventional filtration with collection of organic vapors by means of a high surface area polymeric adsorbent (XAD-2) proved highly efficient for collection of all but the more volatile organic species. The modified sampling system consists of the standard EPA train with the adsorbent sampler (Figure 4-10) located between the filter and the impingers. With this system filterable particulate can be determined from the filter catch and the probe wash according to Method 5, whereas the organic materials present can be determined from the analysis of the filterable particulate and the adsorbent sampler catch. The impingers are only used to protect the dry-gas meter, and their contents are discarded.

4.4.1 POM Emissions

Sample time was extended to two hours to provide a large enough sample for analysis. Following the sampling period, the organic resin module was sealed and returned to the laboratory for analysis. The sampling probe and glassware were washed with a 50-50 mixture of methylene chloride and methanol per laboratory instructions. The filter and wash were also sent to the laboratory following weighing.

These samples were analyzed by capillary-EI, GC-MS utilizing a 30M SE-52 column with hydrogen as a carrier gas. All data were collected by single ion monitoring (SIM) to improve selectivity and sensitivity.

The extractions from the samples received from KVB, reagent blanks, calibration standards and extracts from spiked filters and XAD-2 cartridge blanks were analyzed using GC/MS procedures.

After running all the samples, the areas of the peaks were determined by use of a computer. For the calibration solutions, the peak area of the standard compound is ratioed to the nearest internal standard peak. A least square analysis is performed which provides a slope and intercept used to quantitate the sample solutions. The intercept is taken to represent the quantitation limit. A correlation coefficient is also calculated which gives an indication of the linearity of the calibration. An acceptable curve has a correlation coefficient of at least 0.990.

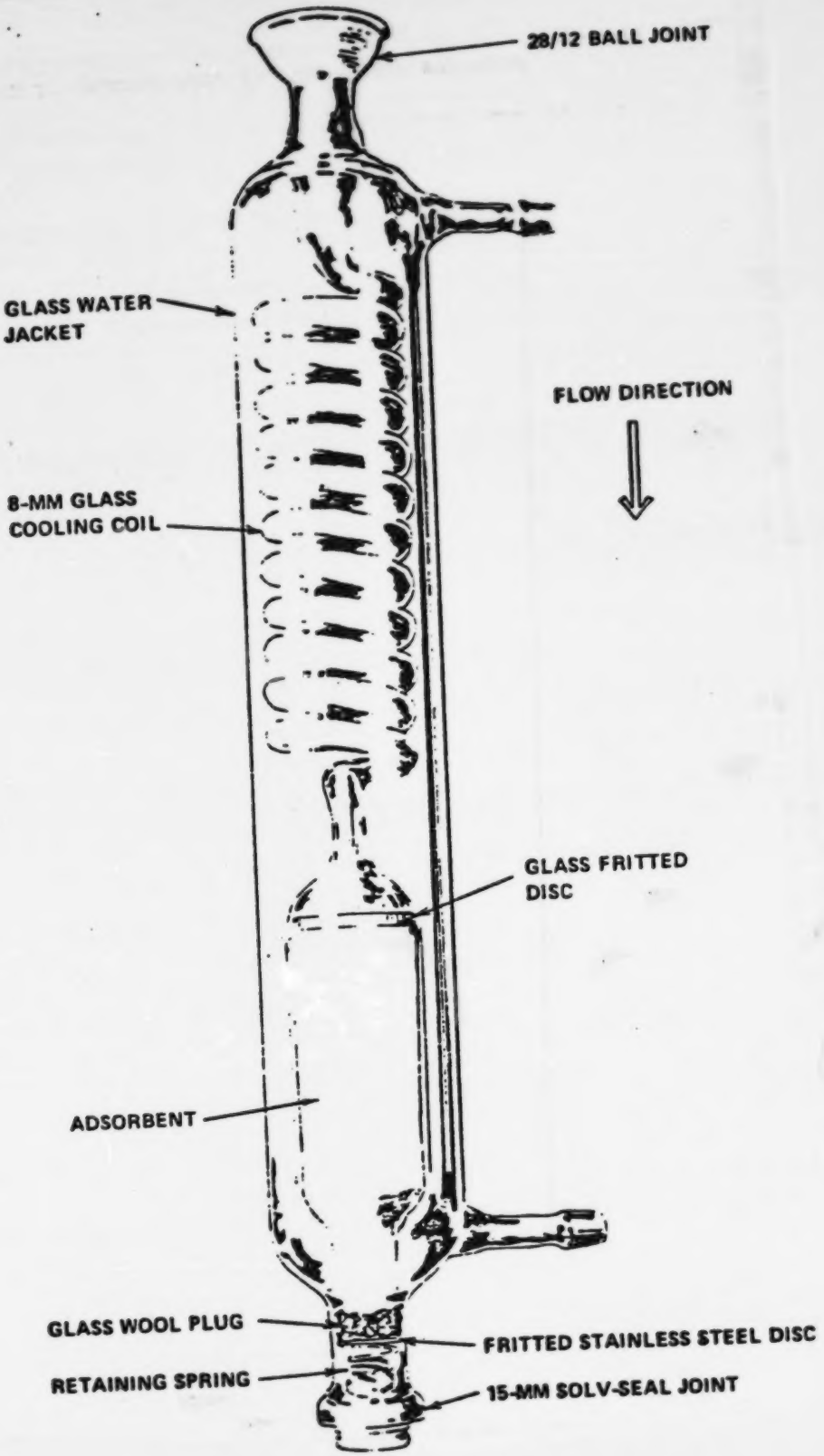

Figure 4-10. Mark III adsorbent sampling system.

The correlations obtained were as follows:

Phenanthrene	0.997
Anthracene	0.997
Fluoroanthrene	0.998
Phyrene	0.998
Benzo(a)anthracene	0.996
Chrysene	0.997
Benzo(e)pyrene	0.997
Benzo(a)pyrene	0.997
Perylene	0.997
Indeno-pyrene	0.994
Benzo(g,h,i)perylene	0.994
Coronene	0.999

Using the computer determined areas for the sample peaks, these areas were ratioed to that of the nearest internal standard. These ratios were then inserted into the appropriate quantitation equation to determine the total amount of the particular POM (expressed in µg) in the sample. Finally, the values for the reagent blank were subtracted from the amount calculated to yield the POM actually in the sample. The results are shown in Table 4-6.

The results of the analyses are presented in µg per total sample. The quantitative detection limit was 0.5 µg, thus samples with POM's present at levels lower than this are reported as <0.5 µg (the standard deviation at lower levels was prohibitively high for accurate quantitation). Samples reporting POM values of ND (none detected) are at a level of less than 0.1 µg (the approximate qualitative detection limit). The standard deviation on points around 0.5 µg averaged around ±20 percent, at levels around 5 µg it averaged around ±15 percent, and at levels above 12 µg the standard deviation averaged around ±10 percent.

The POM analyses for the low NO_x condition are presented in the first six columns of Table 4-6 for the XAD-2 module, the filter/probe wash/cyclone and total. The corresponding data for the unmodified or baseline condition are shown in the last six columns. The POM emissions in the low NO_x condition

TABLE 4-6.

SUMMARY OF POM ANALYSES FOR LOCATION 5 - WOOD-FIRED SPREADER STOKER

POM	Low NO_x Test						Baseline Test					
	XAD-2		Probe Rinse, Cyclone & Filter		Total		XAD-2		Probe Rinse, Cyclone & Filter		Total	
	µg	µg/m^3	µg	µg/m^3	µg	µg/m^3	µg	µg/m^3	µg	µg/m^3	µg	µg/m^3
Phenanthrene	0.7	.70	2.5	2.5	3.2	3.2	0.9	.7	1.6	1.0	2.5	1.7
Anthracene	ND*	ND	<0.4	<.4	<.4	<.4	ND	ND	ND	ND	ND	ND
Methyl Anthracenes/ Phenanthrenes	0.7	.70	2.7	2.7	3.4	3.4	1.0	.8	1.1	.8	2.1	1.6
Fluoranthene	<0.5	<.5	0.8	0.8	0.8<1.3	.8<1.3	ND	ND	<0.5	<.4	<.5	<.4
Pyrene	ND	ND	1.0	1.0	1.0	1.0	ND	ND	<0.5	<.4	<.5	<.4
Methyl Pyrene/Fluoranthene	<0.5	<.5	0.7	.7	.7<1.2	.7<1.2	<0.5	<.4	<0.5	<.4	<1.0	<.8
Benzo(c)phenanthrene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Benz(a)anthracene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Chrysene	ND	ND	<0.5	<.5	<.5	<.5	ND	ND	ND	ND	ND	ND
Methyl Chrysenes	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Dimethylbenz anthracenes	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Benzofluoranthenes	ND	ND	ND	ND	ND	ND	<0.5	<.4	ND	ND	<.5	<.4
Benzo(a)pyrene	ND	ND	<0.6	<.6	<.6	<.6	<0.5	<.4	ND	ND	<.5	<.4
Benzo(e)pyrene	ND	ND	0.6	.6	.6	.6	ND	ND	ND	ND	ND	ND
Perylene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Methylcholanthrenes	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Indeno(1,2,d-cd)pyrene	<1.2	<1.2	<1.2	<1.2	<2.4	<2.4	<1.2	<.9	<1.2	<.9	<2.4	<1.8
Benzo(g,h,i)perylene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Dibenz anthrancenes	ND	ND	<1.2	<1.2	<1.2	<1.2	ND	ND	ND	ND	ND	ND
Dibenzpyrenes	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Coronene	ND	ND	0.1	.1	.1	.1	ND	ND	ND	ND	ND	ND
TOTAL **		1.4<3.6	2.2	2.2 10.6<14.5	2.2	2.2 12.0<18.1	0.1	.1 1.6<3.7	ND	ND 1.8<3.9	0.1	.1 3.4<7.6
Sample volume, m^3	0.993						1.280					

*ND = Not Detected, less than 0.1 µg

**Two totals are shown, e.g., 1.4<3.6 where 1.4 is total of all quantified amounts and 3.6 is total of quantified amounts plus all values indicated as <, which indicates that a compound was observed but cannot be quantified at a value below the amount shown.

were two to three times higher than the emissions at baseline. This large difference could be due more to the fuel change than to the combustion modification although the trend of higher POM with lower NO_x has been observed before (Ref. 1).

A comparison of previous POM measurements of coal- and oil-fired boilers with the present data is provided in Table 4-7. The POM emissions from the hogged fuel boiler in the low NO_x mode were higher than those from the two coal-fired spreaker-stokers and the residual-oil fired unit tested on an EPA thirty-day field test program (Refs. 1,2,3). The baseline POM emissions, however, were approximately equal to those of one coal-fired spreader-stoker (Ref. 1) and were slightly less than the oil-fired unit. In both baseline and low NO_x conditions, the POM emissions from the hogged fuel boiler at Location 5 were well below those of the pulverized coal unit tested on the Thirty-Day program (Ref. 4).

The following conclusions were made based on the present study:

1. POM was higher in the low NO_x mode than under baseline conditions.

2. POM emission for this hogged fuel boiler was greater in the low NO_x configuration than two coal-fired spreader stokers and one residual-oil-fired boiler tested previously by KVB; at baseline, the POM emission was on a par with that of one coal-fired spreaker-stoker and slightly below that of the oil-fired unit.

3. At baseline and in the low NO_x mode, POM emission was well below that of a pulverized coal boiler previously tested.

4. The POM emissions are likely to be dependent on the type of wood burned. The wood fuel composition could not be controlled because of the nature of the wood sources. Therefore, further study is required to determine the exact extent of its influence on POM emissions.

TABLE 4-7. POM EMISSION FROM OIL-, COAL-, AND WOOD-FIRED BOILERS: COMPARISON WITH PRESENT DATA

Location	Boiler Capacity and Type	Fuel	Control Technology	Total POM, $\mu g/m^3$	
				Baseline	Low NO_x
30-Day Tests, Site 1 (Ref. 1)	Spreader-Stoker 12.6Kg/s (100,000 lb/h)	Coal	LEA	1.61<10.8	4.17<10.9
30-Day Tests, Site 2 (Ref. 2)	Residual-Oil-Fired 10.0Kg/s (79,000 lb/h)	No. 6 Oil	SCA (BOOS)	7.59<11.4	4.57<9.68
30-Day Tests, Site 3 (Ref. 4)	Pulverized Coal-Fired 32.8Kg/s (260,000 lb/h)	Coal	SCA + LEA	66.9<70.8	64.57<68.21
30-Day Tests, Site 4 (Ref. 3)	Spreader-Stoker 20.2Kg/s (160,000 lb/h)	Coal	LEA	1.24<2.52	1.035<2.76
Hogged Fuel Boiler Location 5 (Present Data)	Spreader-Stoker 25.2Kg/s (200,000 lb/h)	Wood	LEA + Air Register Adjustment	3.6<7.9	12.0<18.1

SECTION 5.0

REFERENCES

1. Carter, W. A., and Buening, H. J., "Thirty-Day Field Tests of Industrial Boilers, Final Report, Site 1 - Coal-Fired Spreader Stoker," EPA-600/7-80-085a, April 1980.

2. Carter, W. A., and Tidona, R. J., "Thirty-Day Field Tests of Industrial Boilers, Final Report, Site 2 - Residual-Oil-Fired Boiler," EPA-600/7-80-085b, April 1980.

3. Carter, W. A., and Hart, J. R., "Thirty-Day Field Tests of Industrial Boilers, Final Report, Site 4 - Coal-Fired Spreader Stoker," EPA-600/7-80-085d, April 1980.

4. Carter, W. A., and Buening, H. J., "Thirty-Day Field Tests of Industrial Boilers, Final Report, Site 3 - Pulverized Coal-Fired Boiler," EPA-600/7-80-085c, April 1980.

SECTION 6.0

CONVERSION FACTORS

SI Units to Metric or English Units

To Obtain	From	Multiply By
g/Mcal	ng/J	0.004186
10^6 Btu	GJ	0.948
Btu	gm cal	3.9685×10^{-3}
lb/10^6 Btu	ng/J	0.00233
ft	m	3.281
in.	cm	0.3937
ft^2	m^2	10.764
ft^3	m^3	35.314
lb	kg	2.205
Fahrenheit	Celsius	$t_F = 9/5(t_c) + 32$
Fahrenheit	Kelvin	$t_F = 1.8t_K - 460$
psig	Pa	$P_{psig} = (P_{pa})(1.450 \times 10^{-4}) - 14.7$
psia	Pa	$P_{psia} = (P_{pa})(1.450 \times 10^{-4})$
iwg (39.2 °F)	Pa	$P_{iwg} = (P_{pa})(4.014 \times 10^{-3})$
10^6 Btu/hr	MW	3.413
GJ/hr	MW	3.60

To Obtain ppm at 3% O_2 of	Multiply* Concentration in ng/J by
Wood	
CO	2.31
HC	4.05
NO or NO_x	1.41
SO_2 or SO_x	1.01
Oil Fuel	
CO	2.93
HC	5.13
NO or NO_x	1.78
SO_2 or SO_x	1.28
Coal Fuel	
CO	2.69
HC	4.69
NO or NO_x	1.64
SO_2 or SO_x	1.18

*These conversions depend on fuel composition.
The values given are for typical fuels.

English and Metric Units to SI Units

To Obtain	From	Multiply By
ng/J	$lb/10^6$ Btu	430
ng/J	g/Mcal	239
GJ	10^6 Btu	1.055
m	ft	0.3048
cm	in.	2.54
m^2	ft^2	0.0929
m^3	ft^3	0.02832
kg	lb	0.4536
Celsius	Fahrenheit	$t_c = 5/9\ (t_F - 32)$
Kelvin	Fahrenheit	$t_K = 5/9\ (t_F - 32) + 273$
Pa	psig	$P_{pa} = (P_{psig} + 14.7)(6.895 \times 10^3)$
Pa	psia	$P_{pa} = (P_{psia})(6.895 \times 10^3)$
Pa	iwg (39.2 °F)	$P_{pa} = (P_{iwg})(249.1)$
MW	10^6 Btu/hr	0.293
MW	GJ/hr	0.278

To Obtain ng/J of	Multiply* Concentration in ppm @ 3% O_2 by
Wood	
CO	0.432
HC	0.247
NO or NO_x (as NO_2)	0.710
SO_2 or SO_x	0.988
Oil Fuel	
CO	0.341
HC	0.195
NO or NO_x (as NO_2)	0.561
SO_2 or SO_x	0.780
Coal Fuel	
CO	0.372
HC	0.213
NO or NO_x (as NO_2)	0.611
SO_2 or SO_x	0.850

*These conversions depend on fuel composition.
The values given are for typical fuels.

APPENDIX A-1.0

GASEOUS AND PARTICULATE EMISSIONS TEST METHODS AND INSTRUMENTATION

All emission measurement instrumentation was carried in a 9.8 m x 2.4 m (8 x 42 ft) mobile laboratory trailer. A plan view of the trailer is shown in Figure A-1. The gaseous species measurements were made with analyzers located in the trailer.

The emission measurement instrumentation used was the following:

TABLE A-1. EMISSION MEASUREMENT INSTRUMENTATION

Species	Manufacturer	Measurement Method	Model No.
Hydrocarbon	Beckman Instruments	Flame Ionization	402
Carbon Monoxide	Beckman Instruments	IR Spectrometer	865
Oxygen	Teledyne	Polarographic	326A
Carbon Dioxide	Beckman Instruments	IR Spectrometer	864
Nitrogen Oxides	Thermo Electron Co.	Chemiluminescent	10A
Particulates	Joy Manufacturing Co.	EPA Method 5 Train	EPA
Sulfur Dioxide	DuPont Instruments	UV Spectrometer	400
Particle Sizing	Brink	Cascade Impactor	BMS11
Smoke Spot	Bacharach	ASTM 2156-65	RCC
Opacity		EPA Method 9	
Sulfur Oxides (SO_x)		Goksoyr-Ross	

A-1.1 GAS SAMPLING AND CONDITIONING SYSTEM

A flow schematic of the flue gas sampling and analyzing system is shown in Figure A-2. The sampling system uses three positive-displacement diaphragm pumps to continuously draw flue gas from the stack into the

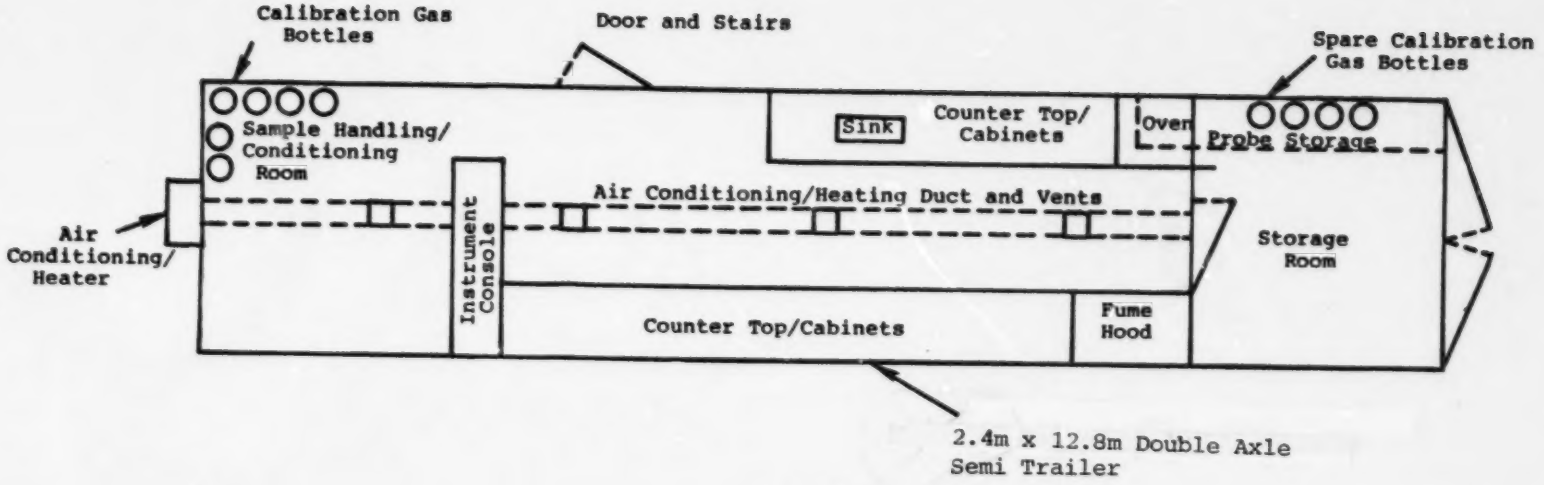

Figure A-1. Instrumentation trailer floor plan.

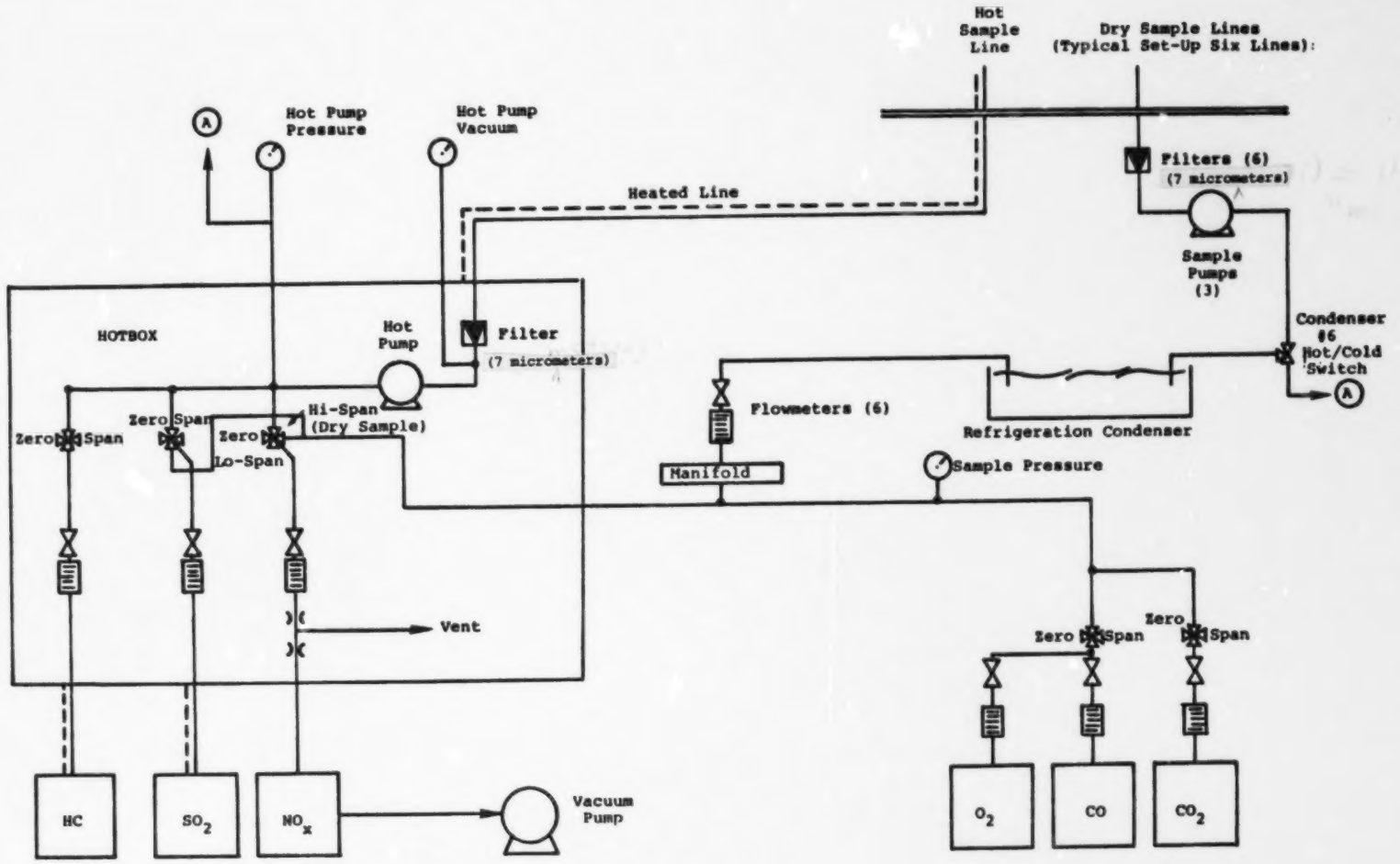

Figure A-2. Flue gas sampling and analyzing system.

laboratory. The sample pumps pull from six unheated sample lines. Selector valves allow composites of up to six points to be sampled at one time. The probes are connected to the sample pumps with 0.95 cm (3/8") or 0.64 cm (1/4") nylon line. The positive displacement diaphragm sample pumps provide unheated sample gas to the refrigerated condenser (to reduce the dew point to 35°F), a rotameter with flow control valve, and to the O_2, NO, CO, and CO_2 instrumentation. Flow to the individual analyzers is measured and controlled with rotameters and flow control valves. Excess sample is vented to the atmosphere.

To obtain a representative sample for the analysis of NO_2, SO_2 and hydrocarbons, the sample must be kept above its dew point, since heavy hydrocarbons may be condensible, and SO_2 and NO_2 are quite soluble in water. For this reason, a separate electrically-heated sample line is used to bring the sample into the mobile laboratory for analysis. The sample line is 0.95 cm (3/8-inch) Teflon line, electrically traced and thermally insulated to maintain a sample temperature of up to 478 K (400°F). A heated diaphragm pump provides hot sample gas to the hydrocarbon, SO_2 and NO_x analyzers.

A-1.2 INSTRUMENTAL CONTINUOUS MEASUREMENTS

The laboratory trailer is equipped with analytical instruments to continuously measure concentrations of NO, NO_2, CO, CO_2, O_2, SO_2, and hydrocarbons. All of the continuous monitoring instruments and sample handling system are mounted in the self-contained mobile laboratory. The entire system requires only connection to on-site water, power, and sampling lines to become fully operational. The instruments themselves are shock mounted on a metal console panel. The sample flow control measurement, and selection, together with instrument calibration are all performed from the console face. Three-pen recorders provide a continuous permanent record of the data taken. The sample gas is delivered to the analyzers at the proper condition and flow rate through the sampling and conditioning system described in the previous section. The sections below describe the analytical instrumentation.

A-1.2.1 Nitric Oxide (NO) and Total Nitrogen Oxides (NO_x)

Both the total nitrogen oxides (NO_x) and nitric oxide (NO) concentrations are measured from a sample gas obtained using a heated sample line at 394 K (250°F). In addition, the nitric oxide concentrations are measured sequentially from samples obtained using the unheated sample line that is connected to the same analyzer in the laboratory trailer. In the latter case, water is first removed from the sample gas by a refrigeration unit. The analytical instrument that is used for all of these measurements is the Thermo Electron Model 10A chemiluminescent gas analyzer.

For NO analyses, the sample gas is passed directly into the reaction chamber where a surplus of ozone is maintained. The reaction between the NO and the ozone produces light energy proportional to the NO concentration which is detected with a photomultiplier and converted to an electrical signal. Air for the ozonator is drawn from ambient through an air dryer and a 10-micrometer filter element.

The chemiluminescent reaction with ozone is specific to NO. To detect NO_2, a thermal converter has been designed to dissociate the NO_2 to NO by the bi-molecular reaction: $2\ NO_2 \rightarrow 2\ NO + O_2$. A model 700 thermal converter is used in conjunction with the chemiluminescent gas analyzer as shown in Figure A-3. The converter is a coil of resistance-heated stainless steel tubing whose purpose is to drive the NO_2/NO ratio to its chemical equilibrium value at the converter temperature and pressure. The unit is designed to operate at a temperature of 923 K (1200 °F) and pressure of .3 kPa (10 torr). For these conditions and typical stack gas O_2 concentrations, the equilibrium NO_2 concentration is 0.2 percent of the total NO_x concentration. Therefore, when a gas sample containing any NO_2 is passed through the converter, essentially all the NO_2 would be converted to NO. The resulting total NO is then measured using the chemiluminescent analyzer and the difference between the actual NO and the "total NO" would be the sample NO_2 concentration. The "total NO" is interpreted as NO_x.

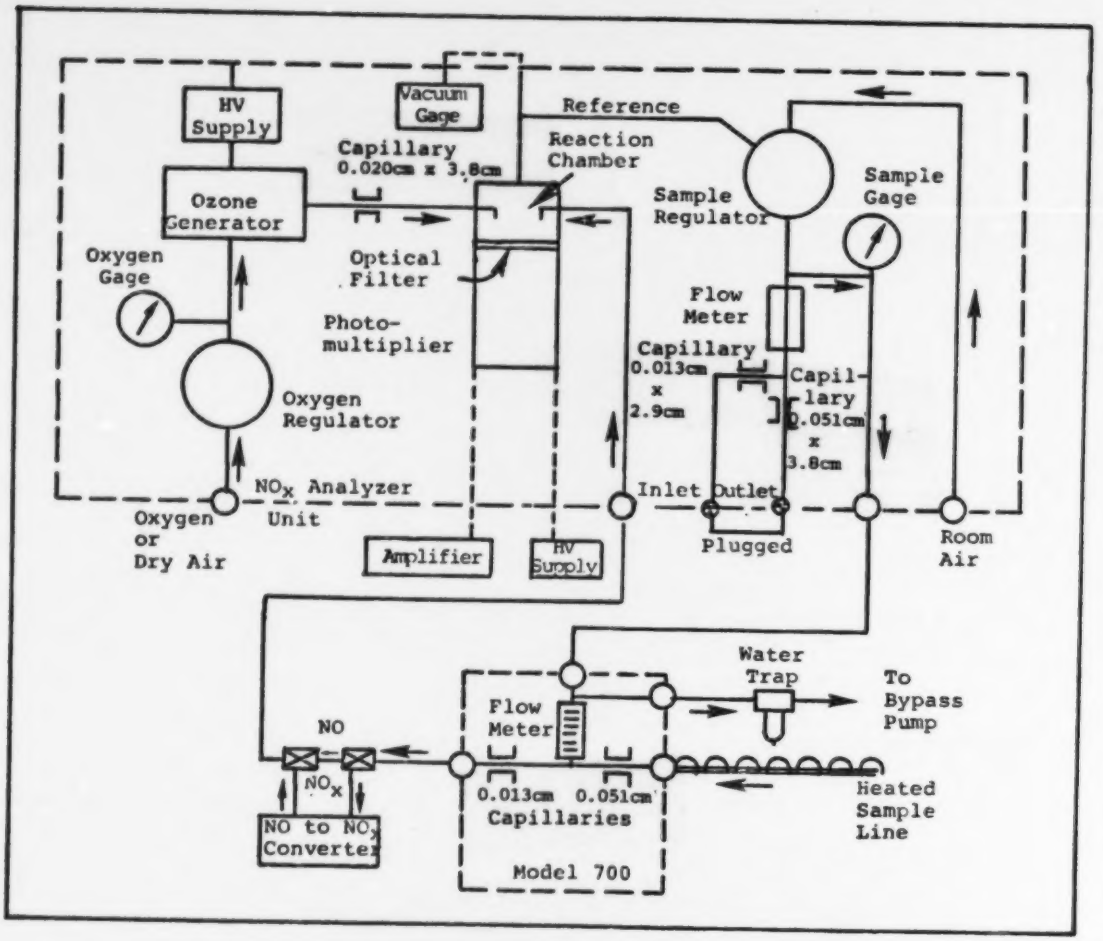

Figure A-3. Schematic of NO_x/NO chemiluminescent analysis system.

NO_2 may react upon contact with H_2O (liquid phase) to form HNO_3 (nitric acid). Under field test conditions, the exhaust gas may contain significant H_2O (depending upon the process and the ambient meteorological conditions), and it is necessary to convert the NO_2 to NO before the H_2O is allowed to condense in the sampling system. By using the heated sample line and the Thermo Electron Model 700 heated NO_x module, NO_2 concentrations will effectively be measured. In reference to Figure A-3, the sample is maintained above the H_2O dew point up to and through the 127 µm (0.005 in.) capillary in the heated module. Downstream of this capillary, the flow network is maintained at 1.3 kPa (10 torr), where the partial pressure of the H_2O in the sample is sufficiently low to prevent any condensation at ambient temperature.

When using the heated system, NO, NO_2, and NO_x are measured on a wet basis. When not using the heated system, a condenser is placed upstream of the analyzer and NO is measured on a dry basis.

Specifications

Accuracy: 1% of full scale

Span stability: ± 1% of full scale in 24 hours

Zero stability: ± 1 ppm in 24 hours

Power requirements: 115 ± 10V, 60 Hz, 1000 watts

Response: 90% of full scale in 1 sec (NO_x mode);
0.7 sec (NO mode)

Output: 4-20 ma

Sensitivity: 0.5 ppm

Linearity: ± 1% of full scale

Vacuum detector operation

Range: 2.5, 10, 25, 100, 250, 1000, 2500, 10,000 ppm full scale

A-1.2.2 Carbon Monoxide and Carbon Dioxide (CO and CO_2)

Carbon monoxide and carbon dioxide concentrations are measured using Beckman Model 864 and 865 short-path-length nondispersive infrared analyzers (see Figure A-4). These instruments measure the differential in infrared energy absorbed from energy beams passed through a reference cell (containing a gas selected to have minimal absorption of infrared energy in the wavelength absorbed by the gas component of interest) and a sample cell through which the sample gas flows continuously. The differential absorption appears as a reading on a scale of 0% to 100% and is then related to the concentration of the species of interest by calibration curves supplied with the instrument. A linearizer is supplied with each analyzer to provide a linear output over the range of interest. The operating ranges for the CO analyzer are 0-100 and 0-2000 ppm, while the ranges for the CO_2 analyzer are 0-5% and 0-20%.

Specifications

Span stability: ± 1% of full scale in 24 hours

Zero stability: ± 1 ppm in 24 hours

Ambient temperature range: 273 to 322 K (32°F to 120°F)

Line voltage: 115 ± 15V rms

Response: 90% of full scale in 0.5 or 2.5 sec

Linearity: Linearizer board installed for one range

Precision: ± 1% of full scale

Output: 4-20 ma

A-1.2.3 Oxygen (O_2)

A Teledyne Model 326A oxygen analyzer is used to automatically and continuously measure the oxygen content of the flue gas sample. The analyzer utilizes a micro-fuel cell which is specific for oxygen, has an absolute zero, and produces a linear output from zero through 25 percent oxygen. The micro-fuel cell is a sealed electrochemical transducer with no electrolyte to change or electrodes to clean. Oxygen in the flue gas diffuses through a Teflon membrane and is reduced on the surface of the cathode. A corresponding

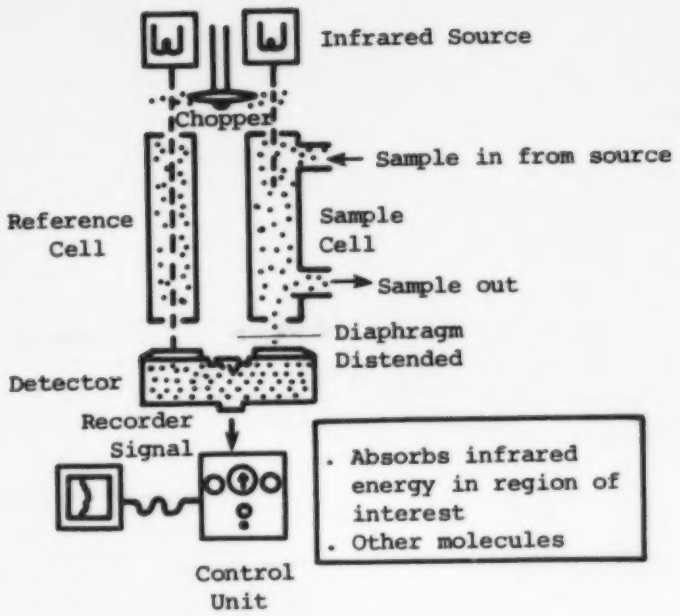

Figure A-4. Schematic of NDIR analyzer.

oxidation occurs at the anode internally and an electric current is produced that is proportional to the concentration of oxygen. This current is measured and conditioned by the instrument's electronic circuitry to give an output in percent O_2 by volume for operating ranges of 0% to 5%, 0% to 10%, and 0% to 25%.

Specifications

Precision: ± 1% of full scale

Response: 90% in less than 40 sec

Sensitivity: 1% of low range

Linearity: ± 1% of full scale

Ambient temperature range: 273 K to 325 K (32°F to 125°F)

Fuel cell life expectancy: 40,000% +-hrs

Power requirement: 115 VAC, 50-60 Hz, 100 watts

Output: 4-20 ma

A-1.2.4 Total Hydrocarbons (HC)

Hydrocarbon emissions are measured using a Beckman Model 402 high-temperature hydrocarbon analyzer. The analyzer utilizes the flame ionization method of detection which is a proven technique for a wide range of concentrations (0.1 to 120,000 ppm). A flow schematic of the analyzer is presented in Figure A-5. The sensor is a burner where a regulated flow of sample gas passes through a flame sustained by regulated flows of air and a premixed hydrogen/nitrogen fuel gas. Within the flame the hydrocarbon components of the sample stream undergo a complex ionization that produces electrons and positive ions. Polarized electrodes collect these ions, causing current to flow through electronic measuring circuitry. Current flow is proportional to the rate at which carbon atoms enter the burner.

The analysis occurs in a temperature-controlled oven. The sample is extracted from the stack with a stainless steel probe which has been thermally treated and purged to eliminate any hydrocarbons existing in the probe itself. An insulated heat-traced teflon line is used to transfer the sample

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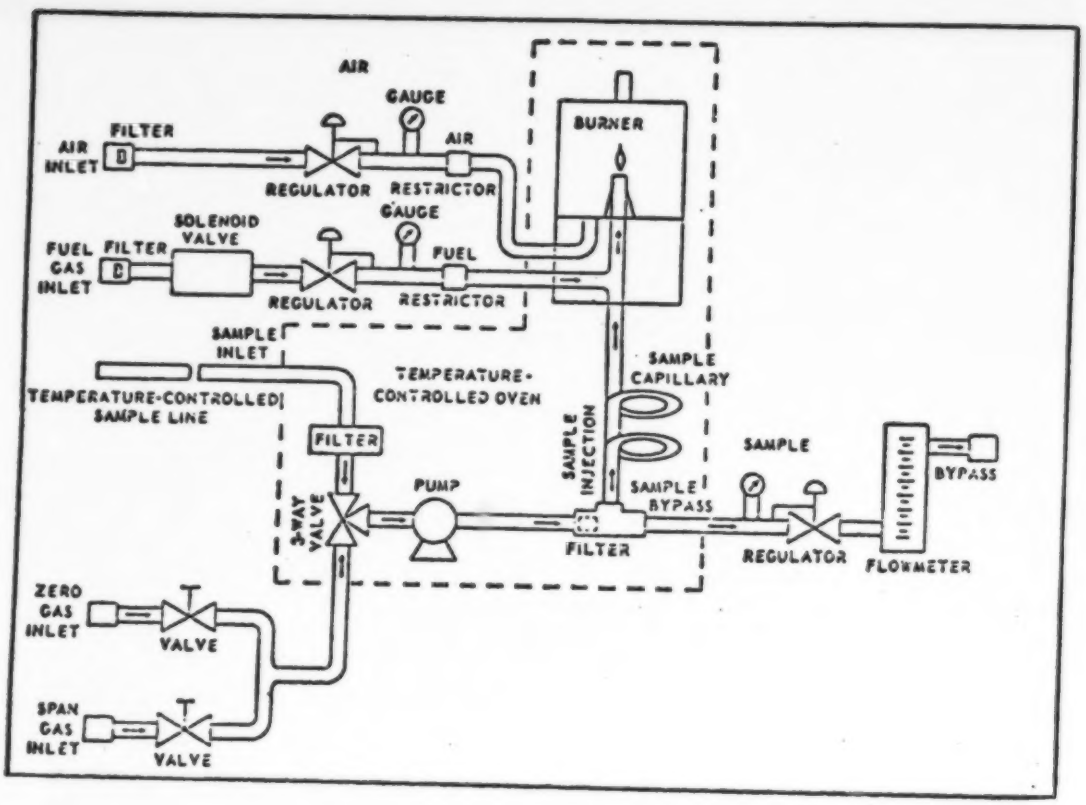


Figure A-5. Flow schematic of hydrocarbon analyzer (FID).

to the analyzer. The entire heated network is maintained at a temperature sufficient to prevent condensation of heavier hydrocarbons.

The flame ionization detector is calibrated with methane, and the total hydrocarbon concentration is reported as the methane equivalent. FID's do not respond equally to all hydrocarbons but generally provide a measure of the carbon-hydrogen bonds present in the molecule. The FID does not detect pure carbon or hydrogen.

Specifications

Full-scale sensitivity: adjustable from 5 ppm CH_4 to 10% CH_4

Ranges: Range multiplier switch has 8 positions: X1, X5, X10, X50, X100, X500, X1000, and X5000. In addition, span control provides continuously variable adjustment within a dynamic range of 10:1

Response time: 90% full scale in 0.5 sec

Precision: ± 1% of full scale

Electronic stability: ± 1% of full scale per 24 hours with ambient temperature change of less than 5.6 K (10°F)

Reproducibility: ± 1% of full scale for successive identical samples

Analysis temperature: ambient

Ambient temperature: 273 K to 317 K (32°F to 100°F)

Output: 4-20 ma

Air requirements: 250 to 400 cc/min of clean, hydrocarbon-free air, supplied at 2.07×10^5 to 1.38×10^6 n/m^2 (30 to 200 psig)

Fuel gas requirements: 75 to 80 cc/min of fuel consisting of 100 percent hydrogen supplied at 2.07×10^5 to 1.38×10^6 n/m^2 (30 to 200 psig)

Electric power requirements: 120 V, 60 Hz

Automatic flame indication and fuel shut-off valve

A-1.2.5 Sulfur Dioxide (SO_2)

A Dupont Model 400 photometric analyzer is used for measuring SO_2. This analyzer measures the difference in absorption of two distinct wavelengths (ultraviolet) by the sample. The radiation from a selected light source passes through the sample and then into the photometer unit where the radiation is split by a semi-transparent mirror into two beams. One beam is directed to a phototube through a filter which removes all wavelengths except the "measuring" wavelength, which is strongly absorbed by the constituent in the sample. A second beam falls on a reference phototube, after passing through an optical filter which transmits only the "reference" wavelength. The latter is absorbed only weakly, or not at all, by the constituent in the sample cell. The phototubes translate these intensities to proportional electric currents in the amplifier. In the amplifier, full correction is made for the logarithmic relationships between the ratio of the intensities and concentration or thickness (in accordance with Beer's Law). The output is therefore linearly proportional, at all times, to the concentration and thickness of the sample. The instrument has a lower detection limit of 2 ppm and full scale ranges of 0-200 and 0-2000 ppm.

Specifications

Noise: Less than 1/4%

Drift: Less than 1% full scale in 24 hours

Accuracy: (± 1% of analyzer reading) + (± 1/4% of full scale range)

Sample cell: 304 stainless steel, quartz windows

Flow rate: 0.05 dm^3/s (6 cfh)

Light source: Either mercury vapor, tungsten, or "Osram" discharge type lamps

Power rating: 500 watts maximum, 115 V, 60 Hz

Reproducibility: 1/4% of scale

Electronic response: 90% in 1 sec

Sample temperature: 378 K (220°F)

Output: 4-20 ma d.c.

A-1.3 PARTICULATE MATTER TOTAL MASS CONCENTRATION

Particulate matter is collected by filtration and wet impingement in accordance with US-EPA Method No. 5. Nomograph techniques are utilized to select the proper nozzle size and to set the isokinetic flow rates.

Gas samples for particulate sampling can be taken from the same sample port as those for gas analysis and passed through the Joy Manufacturing Company Portable Effluent Sampler. This system, which meets the EPA design specifications for Test Method 5, Determination of Particulate Emissions from Stationary Sources (Federal Register, Volume 36, No. 27, page 24888, December 24, 1971, and revisions thereof) is used to perform both the initial velocity traverse and the particulate sample collection.

Dry particulates are collected in the heated case that may contain a cyclone to separate particles larger than 5 μm and a 110-mm glass-fiber filter to retain particles as small as 0.3 μm. Condensible particulates are collected in four Greenburg-Smith impingers immersed in a chilled water bath.

The sampling probe is positioned through an exhaust port and attached to the sampling box. The probe consists of a sampling nozzle, heated probe, gaseous probe, thermocouple, and pitot tube. The ball joint from the heated probe connects to the cyclone and glass filter holder assembly. These assemblies are positioned in the heated sampling box which is maintained at 394 K (250°F), in order to eliminate condensation. The sample then passes from the heated section to four Greenburg-Smith impingers immersed in an ice bath. Only the second impinger has the original tip, the other three have had the tip removed to decrease the pressure drop through them. The first and second impingers are filled with 150 milliliters of distilled/deionized water. The third impinger is left dry. The fourth impinger is filled with approximately 200 grams of indicating silica gel to remove entrained water. The use of

silica gel assures that a dry sample is delivered to the meter box. After sampling, the spent silica gel is discarded and not used for any further analysis.

An umbilical cord connects the last impinger, the pitot tube, and the heating elements to the meter box which is located in a convenient place within 15 m of the sampling ports. The meter box contains a vacuum pump, regulating valves, instantaneous and integrating flow meters, pitot tube manometers, vacuum gauge, and electrical controls.

Particulate matter (solids and condensibles) is collected in three discrete portions by the sampling train: the probe and glassware upstream of the filter; the filter; and the wet impingers. The probe and glassware are brushed and rinsed with acetone; the matter is captured for gravimetric analysis. The probe and glassware are then rinsed with distilled water and the rinsings transferred to a second container for analysis. The filter is desiccated and analyzed gravimetrically. The combined impinger liquid is heated to drive off uncombined water and the residue retained for analysis. The particulate matter analysis is illustrated schematically in Figure A-6.

US EPA Method 5 considers the particulate matter captured in containers (1) and (3); the filter, probe brushing, and probe acetone rinse. As EPA source standards are based on solid particulates only, care is taken to differentiate between solid and the total (including condensible) particulates. The water wash is performed because KVB's test experience has shown that a significant amount of water-soluble material may sometimes be captured by the probe.

The dry sample volume is determined with a dry test meter at a measured temperature and pressure and then converted to standard conditions. The volume of condensed water in the impingers is measured in milliliters and the corresponding volume of water vapor is then computed at standard conditions. The dry sample volume and water vapor volume are then summed to give the total sample volume. The dry sample volume is used in the data reduction procedures.

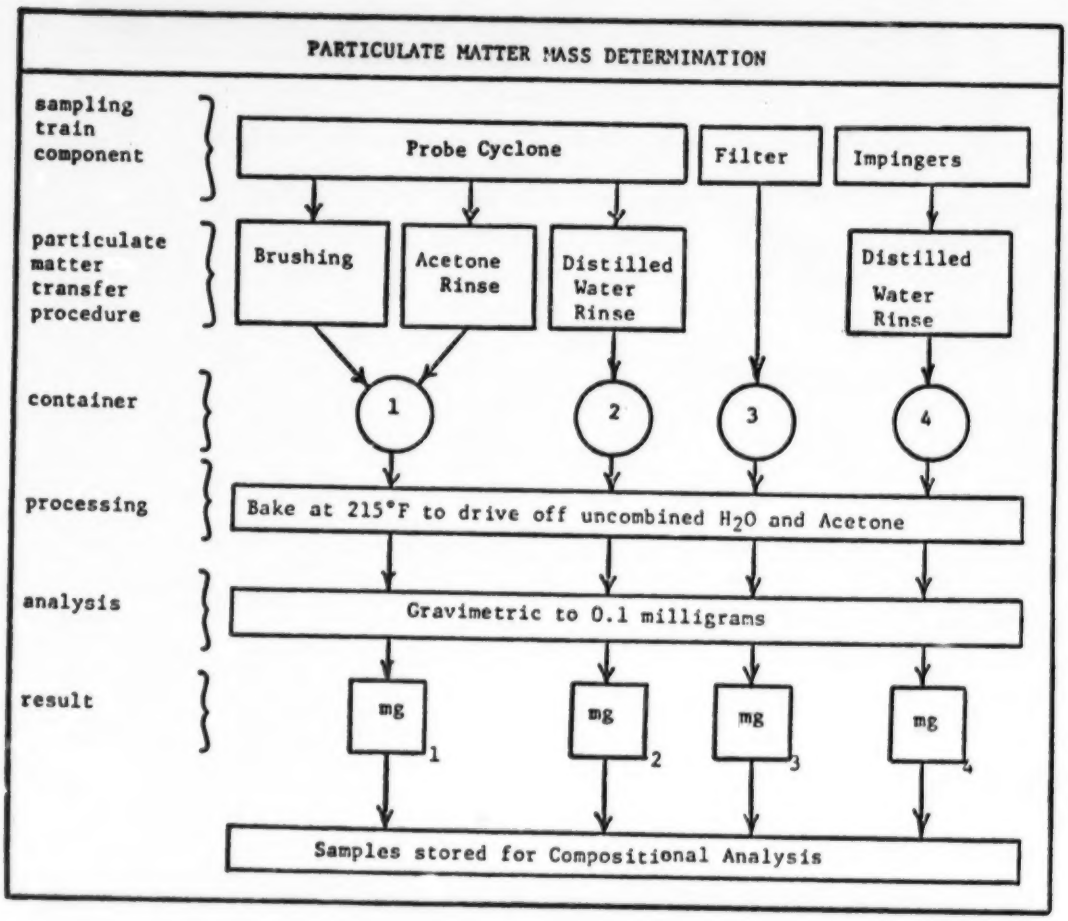


Figure A-6. Processing and analyzing particulate matter.

A point of interest is the method chosen to calculate particulate emissions in ng/J or lb/10^6 Btu from the experimental data. The particulate sampling train, properly operated, yields particulate mass per unit flue gas volume. Having measured g/m^3, it is necessary to establish the flue gas volume per unit heat input if emissions in ng/J are desired. The original Method 5 involved determining a velocity traverse of the stack, the cross-sectional area, the flue flow rate, and fuel heating value. A revised and more accurate method has been promulgated by the Environmental Protection Agency that utilizes a fuel analysis (carbon content, hydrogen content, high heating value, etc.) and the measured O_2 in the exhaust to calculate the gas volume generated in liberating 1.055 GJ (a million Btu's). The velocity traverse approach generally results in a 20 to 30 percent higher value and is believed to be less accurate.

A-1.4 SMOKE SPOT

On combustion equipment where smoke numbers normally are taken, such as oil-fired boilers, KVB, Inc. determines the smoke number using test procedures according to ASTM Designation: D 2156-65. The smoke number is determined at each combustion modification setting of the unit. Examples are baseline, minimum excess air, low load, etc., and whenever a particulate concentration is measured.

Smoke spots are obtained by pulling a fixed volume of flue gas through a fixed area of a standard filter paper. The color (or shade) of the spots that are produced is visually matched with a standard scale. The result is a "Smoke Number" which is used to characterize the density of smoke in the flue gas.

The sampling device is a hand pump similar to the one shown in Figure A-7 . It is a commercially available item that can pass 36,900 $\pm$ 1650 cu cm of gas at 289K and 1 atmosphere pressure through an enclosed filter paper for each 6.5 sq cm effective surface area of the filter paper.

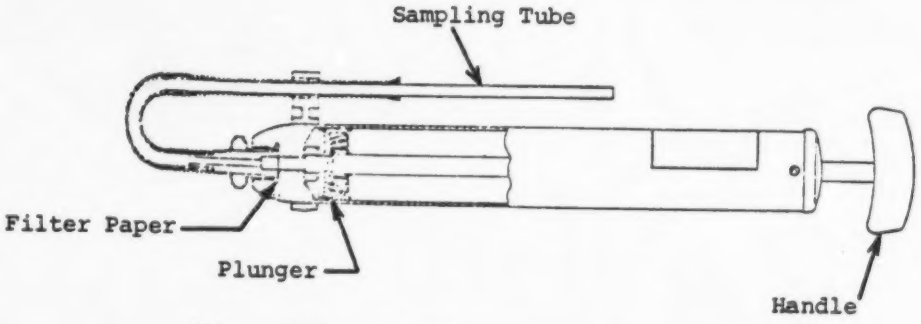


Figure A-7. Field-service-type smoke tester.

The smoke spot sampler is provided with a motor-driven actuator to ensure a constant sampling rate independent of variations in stroke rate that can occur when the sampler is operated manually.

The smoke scale required consists of a series of ten spots numbered consecutively from 0 to 9, and ranging in equal photometric steps from white through neutral shades of gray to black. The spots are imprinted or otherwise processed on white paper or plastic stock having an absolute surface

reflectance of between 82.5 and 87.5%, determined photometrically. The smoke scale spot number is defined as the reduction (due to smoke) in the amount of light reflected by a soiled spot on the filter divided by 10.

Thus the first spot, which is the color of the unimprinted scale, is No. 0. In this case there is no reduction in reflected incident light directed on the spot. The last spot, however, is very dark, reflecting only 10% of the incident light directed thereon. The reduction in reflected incident light is 90%, and this spot is identified as No. 9. Intermediate spot numbers are similarly established. Limits of permissible reflectance variation of any smoke scale spot will not exceed $\pm$ 3% relative reflectance.

The test filter paper is made from white filter paper stock having absolute surface reflectance of 82.5 to 87.5%, as determined by photometric measurement. When making this reflectance measurement, the filter paper is backed by a white surface having absolute surface reflectance of not less than 75%.

When clean air at standard conditions is drawn through clean filter paper at a flow rate of 47.6 cu cm per sec per sq cm effective surface area of the filter paper, the pressure drop across the filter paper falls between the limits of 1.7 and 8.5 kPa (1.3 and 6.4 cm of mercury).

The sampling procedure is exactly that specified in D 2156. A clean, dry, sampling pump is used. It is warmed to room temperature to prevent condensation on the filter paper. When taking smoke measurements in the flue pipe, the intake end of the sampling probe is placed at the center line of the flue. When drawing the sample, the pressure in the flue gas stream and the sampler is allowed to equalize after each stroke.

The smoke density is reported on the Mobile Lab Data Sheet as the Smoke Spot Number on the standard scale most closely corresponding to test spot. Differences between two standard Smoke Spot Numbers are interpolated to the nearest half number. Smoke Spot Numbers higher than 9 are reported as "Greater than No. 9."

This procedure is deemed to be reproducible to within $\pm$ 1/2 of a Smoke Spot Number under normal conditions where no oily stain is deposited on the disk.

KVB's field experience with industrial boilers has been that the human factor involved in the interpretation of the smoke spot by an experienced observer does not cause a significant lack of precision.

A-1.5 OPACITY

Opacity readings are taken by a field crew member who is a certificated graduate of a U.S. Environmental Protection Agency approved "Smoke School". Observations are made at the same time that particulate measurements are made and as often in addition as deemed necessary to gather the maximum amount of information. The procedures set forth in EPA Method 9, "Visual Determinations of the Opacity of Emissions for Stationary Sources" are followed.

Observations are made and recorded at 15 second intervals while particulate concentration is being measured and after the unit has stabilized at other times. Before beginning observations, the observer determines that the feedstock or fuel is the same as that from which the sample was taken for the fuel analysis.

Before beginning opacity observations, the observer makes arrangements with the combustion unit operator to obtain the necessary process data for the standard KVB Control Room Data Sheet. The control room data are recorded for the entire period of observations, as is customarily done by KVB during an emissions test. The process unit data that are obtained include:

a. Production rates
    1. maximum rated capacity
    2. actual operating rate during test
b. Control device data
    1. recent maintenance history
    2. cleaning mechanism and cycle information

The observer requests the appropriate plant personnel to briefly review and comment on the opacity measurements and process data and the observer comments on:

a. the basis for choosing the observation periods used.
b. why it is believed the periods chosen constitute periods of greatest opacity.
c. why the observations span a time period sufficient to characterize the opacity.

Consideration is given to postponing the EPA Method 5 particulate tests during periods of cloudy or rainy weather because of the inability of the observer to monitor the smoke.

A-1.5.1 Sulfur Oxides (SO_x)

Goksoyr-Ross Method--Wet Chemical Method

The Goksoyr-Ross Controlled Condensate (G/R) method is used for the wet chemical SO_2/SO_3 determination. It is a desirable method because of its simplicity and clean separation of particulate matter, SO_2 and H_2SO_4 (SO_3). This procedure is based on the separation of H_2SO_4 (SO_3) from SO_2 by cooling the gas stream below the dew point of H_2SO_4 but above the H_2O dew point. Figure A-8 illustrates schematically the G/R test system.

Particulate matter is first removed from exhaust gas stream by means of a quartz glass filter placed in the heated glass filter holder. Tissue-quartz filters are recommended because of their proven inertness to H_2SO_4. The filter system is heated by a heating tape so that the gas out temperature of 533 K (500°F) is maintained. This temperature is imperative to ensure that none of the H_2SO_4 will condense in the filter holder or on the filter.

The condensation coil where the H_2SO_4 is collected is cooled by water which is maintained at 333 K (140°F) by a heater/recirculator. This temperature is adequate to reduce the exhaust gas to below the dew point of H_2SO_4.

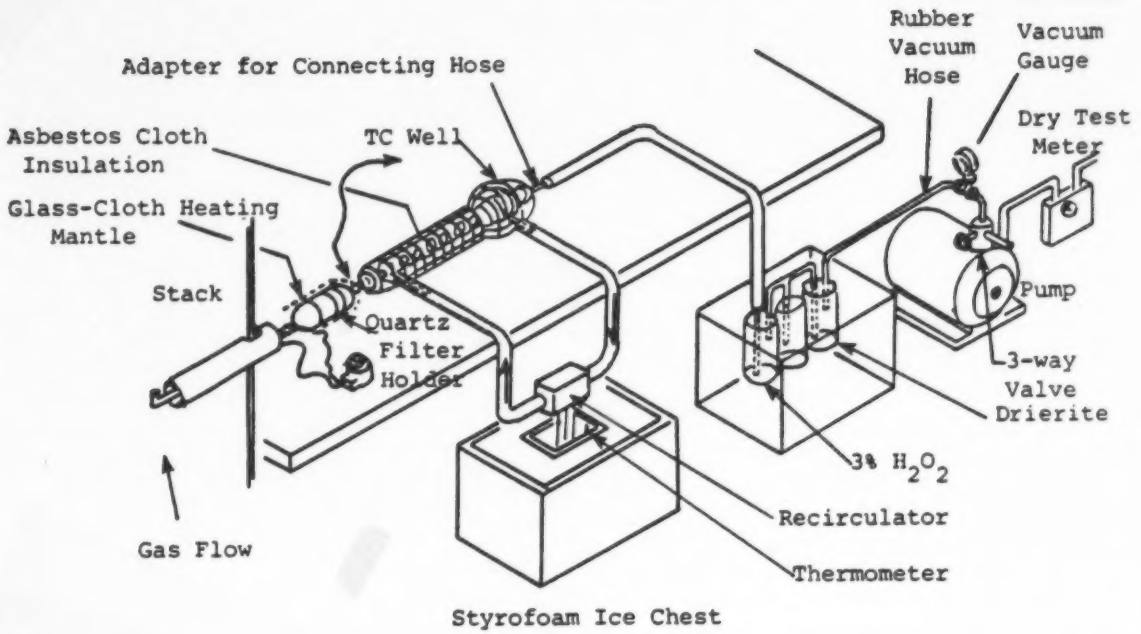


Figure A-8. Schematic of Goksoyr-Ross controlled condensation system (CCS).

Three impingers are shown in Figure A-8. The first impinger is filled with 3 percent H_2O_2 to absorb SO_2. The second impinger is to remove carryover moisture and the third contains Drierite and a thermometer to measure the exhaust gas temperature to the dry gas meter and pump. The sampling rate is 0.04 dm^3/s (0.08 cfm).

A-1.5.2 Analysis Procedure

For both SO_2 and H_2SO_4 determination, the analytical procedure is identical. The H_2SO_4 sample is washed from the back part of the filter holder and the coil using a 5 percent isopropyl alcohol solution. The sample from the first impinger which is assumed to be absorbed and reacted SO_2 in the form of H_2SO_4 is recovered with distilled water washing. The amount of H_2SO_4 in the condensate from the coil and from the H_2O_2 impinger is measured by H+ titration. Bromphenol Blue is used with NaOH as the titrant.

A-1.6 PARTICLE SIZE DISTRIBUTION

Particle size distribution was determined using a Brink Model BMS-11 cascade impactor (Figure A-9).

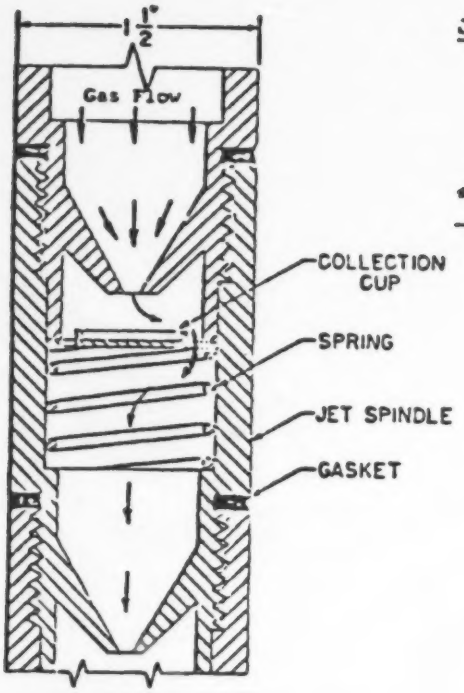
A-1.6.1 Design

The Brink sampling probe is a modular cascade impactor apparatus suitable for sampling dust in a wide range of flue gas conditions. The primary components are a cyclone separator, a cascade impactor, an absolute filter, and a critical orifice. The cascade impactor comes with sampling tips of various sizes and is constructed of 316 stainless steel. The impactor consists of a number of stages arranged in series. From one to five stages can be used. Each impactor stage has an orifice and a collection cup. These are shown in Figure A-9. The orifice diameter and the distance between the orifice and the cup determine the particle collection characteristics of the stage. These dimensions are listed in the table in Figure A-9. An absolute filter follows the final impactor stage. This back-up filter was a Gelman Type A Glass Fiber Filter. Special collection substrates (e.g., glass fiber, aluminum foil, etc.) placed on the collection plates can be used. The stack

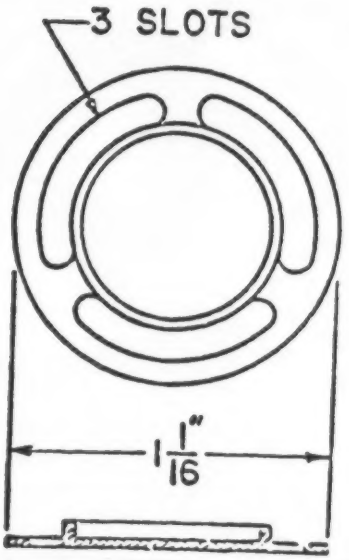
DIMENSIONS OF CASCADE IMPACTOR JETS

	Dimensions, Cm	
Jet No.	Jet Diam.	Spacing of Jet Opening*
1	0.249	0.747
2	0.1775	0.533
3	0.1396	0.419
4	0.0946	0.282
5	0.0731	0.220

*From collection cup surface.



The in-line impactor has five stages. Particles in the range of 0.3 to 3.0 microns are collected by successive impingement.



Collection cups are positioned so that the distance from the jet decreases as the jet diameter becomes smaller. Annular slots around cup minimize turbulence.

Figure A-9. Design of a single stage from a Brink-type cascade impactor.

sampler is designed to operate at 2.8 ℓ/min or less. An ideal flow rate is around 2 ℓ/min.

A-1.6.2 Operation

The impactor will be carefully loaded with the stage cups and the preweighed stage substrates. The Brink should be tightened with wrenches to make certain the high temperature No. 116 asbestos gaskets are sealed. The appropriate nozzle for isokinetic sampling is now added. The flue gas temperature should be above the dew point but less than 450°F. After mounting the impactor on the preheated sample probe, it will be inserted into the duct to be preheated for at least 30 minutes. The inlet nozzle will be pointed downstream of the flow during the heating phase. A predetermined flow rate is established immediately and is maintained constant, since any attempt to modulate flow to compensate for changes in the duct flow rate to provide isokinetic sampling will destroy the utility of the data by changing the cut points of the individual stages. Establishment of the correct flow rate quickly is especially important for the short sampling times typical of high dust loaded streams.

Sample times will normally vary from 5 to 45 minutes depending on the dust loading. A total sample weight of <8 mg per stage should be collected. The stages of the Brink impactor will yield cuts of 0.25, 0.50, 1.0, 1.5, and 2.5 μm. After the sampling cycle has been completed, the impactor is cooled and disassembled. Proper disassembly is critical to make sure the collected material stays where it originally impacted. After the desiccating of the collection media, weighing is performed to determine the net particle accumulations.

A-1.6.3 Data Presentation

To determine the concentration of particulates for any size range, first determine the percentage of total particulates for each stage. Then the cumulative percentage is determined beginning with the last stage of the impactor. By plotting the effective cutoff diameter and the cumulative percent on logarithmic probability graph paper, the particle concentration by weight for any specific size can be determined.